Soil compaction by wheeling: change in soil suction due to compression

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Summary

Soil compaction due to traffic has been increasingly recognized as a considerable problem facing intensive agriculture. Most of the models used to estimate soil deformation during the passage of machines are based on the concept of total stress: then they have neglected an important stress variable for unsaturated soils, i.e. the matrix suction. The aim of the present work is to evaluate the validity of this hypothesis by studying suction variation during a static compression test. A standard oedometer cell equipped with a tensiometer was used to measure soil suction *in situ* for different vertical stresses. Measurements were carried out on remoulded soil samples obtained by compacting a loamy soil at different initial water suctions (< 100 kPa). The results showed that the suction remained almost constant until a stress threshold value σ_t beyond which the suction decreased as the stress increased. This stress threshold increased with the initial suction. These results corroborated the hypothesis of a constant suction during deformation usually assumed to model soil compaction during traffic for soils with suction higher than 20 kPa. The results obtained highlighted the effect of soil structure on the stress threshold: σ_t was found to be higher for soil samples with initial aggregates < 2 mm for those with initial aggregates < 0.4 mm. This was interpreted at pore scale by comparing qualitatively the evolution of pore-size distribution and the expected distribution of water in the pores. This interpretation was based on pore-size distribution measurement by mercury intrusion.

Résumé

Le tassement des sols par les engins agricoles est un problème important auquel est confrontée l’agriculture intensive. La plupart des modèles utilisés pour prévoir la déformation d’un sol sous le passage d’un engin est basée sur le concept de contrainte totale. Ils négligent alors une variable importante pour les sols non saturés : la succion du sol. L’objectif de cette étude est d’évaluer les conditions d’application d’une telle hypothèse à partir de l’observation des variations de succion lors d’un test de compression en laboratoire. Un dispositif oedométrique standard équipé d’un tensiomètre dans la cellule de compression a permis de mesurer *in situ* la succion du sol lors de l’application de différentes contraintes verticales. Les mesures ont été réalisées sur un sol de limon tamisé et porté à différentes succion initiales (< 100 kPa). Les expériences montrent que la succion reste pratiquement constante jusqu’à une valeur seuil de contrainte verticale σ_t au-delà de laquelle elle décroît à mesure que la contrainte verticale augmente. Ce seuil de contrainte verticale σ_t augmente avec la succion initiale. Ces résultats corroborent l’hypothèse d’une succion constante au cours de la compression utilisée le plus souvent dans les modèles de compactage mais pour des succions supérieures à 20 kPa. Les résultats mettent en évidence un effet de la structure initiale des échantillons : le seuil de

contrainte verticale σ_t est supérieur pour des sols tamisés < 2 mm par rapport à ceux tamisés < 0.4 mm. Ceci a été interprété à l'échelle des pores en comparant l'évolution des distributions de taille de pore et la distribution supposée de l'eau dans ces pores. Cette interprétation repose sur des mesures de porosimétrie à mercure.

1. Introduction

Soil compaction caused by agricultural machines greatly modifies the structure (tilled layers and underlying layers). Because of its persistence, compaction of subsoil layers can be considered as a long-term degradation but compaction concerns also surface layers because it impacts significantly on vegetable production (root penetration) and environment (runoff and greenhouse gas emissions) (O'Sullivan & Simota, 1995). Compaction is defined as the deformation process of cultivated soil in which a rut is formed on the surface, decreasing bulk porosity under the wheels of agricultural machines. Changes in pore shape due to shearing also occur. Numerical analyses using the Finite Element Method have been used to simulate soil compaction on the basis of stress-strain behaviour and the mechanical parameters involved have generally been estimated from laboratory tests. Gysi (2001) modelled the compaction of a loamy soil under heavy wheel traffic using the Modified Cam-Clay model in PLAXIS code (PLAXIS, 1998). Kirby (1994) simulated the deformation of a clay agricultural soil using a simple extension to the Modified Cam-Clay model. These numerical works showed that the critical-state models originally developed for saturated soils can be used for unsaturated soil using constant mechanical parameters measured in unsaturated conditions. However, some authors (Burland, 1956; Jennings & Burland, 1962) showed that classical soil mechanics for saturated soils are unable to explain the mechanical behaviour of unsaturated soils satisfactorily. To achieve this it would be necessary to consider two independent variables: net stress ($\sigma - u_a$) where σ is the total stress and u_a is the pore-air pressure and suction $s = u_a - u_w$, where u_w is the pore-water pressure. In particular, it can be assumed that for agricultural conditions at low initial suction (< 100 kPa) and low vertical stress (< 400 kPa), the air in the pore space joins up and ultimately interconnects with the atmosphere. Under these conditions, u_a is equal to zero and the two stress variables become the total stress (σ) and pore-water pressure (u_w). Different constitutive models have also been proposed for unsaturated soils for geotechnical purposes (Alonso *et al.*, 1990; Wheeler & Sivakumar, 1995; Cui & Delage, 1996) and for compaction of agricultural soils (Richards, 1992).

The present work deals with the variation of soil matrix suction under the application of stress due to the passage of vehicle in soils used for agriculture. In comparison to soils used for geotechnical applications, cultivated soils are more porous especially in top soil layers. Compaction problems occur in wet conditions usually for suctions < 100 kPa, the loading is short (the loading time t < 0.1 s) and vertical stresses σ are generally lower than 400 kPa. Some authors studied the soil suction of samples under different levels of compression stress in conditions relevant for compaction of agricultural (Larson & Gupta, 1980; Wulfsohn *et al.*, 1998; Tarantino & Tombola, 2005; da Veiga *et al.*, 2007). Soil suction remained quasi-constant or increased for compressive stresses lower than a given stress threshold (Larson & Gupta, 1980; Wulfsohn *et al.*, 1998; da Veiga *et al.*, 2007). This stress threshold was related to the saturation degree of soils (Larson & Gupta, 1980). On the contrary, Tarantino & Tombola (2005) studied the change of suction after compaction on clay and reported that suction decreased systematically. Peng *et al.* (2004) showed that continuous soil suction monitoring during compression involves non equilibrium effects due to air and water drainage processes. Peng *et al.*(2004) and Krümmelbein *et al.* (2008) showed the effects of loading time on the soil suction change in the transient regime which follows the stress application. These changes were related to the precompression stress (Peng *et al.*, 2004).

The present work examines the effects of initial soil suction and initial soil structure on soil suction changes under static compression after equilibrium, by carrying out oedometer compression tests with measurements of sample soil suction based on techniques developed for unsaturated soils in geotechnical engineering (Dineen & Burland, 1995; Ridley & Burland, 1996; Tarantino *et al*., 2000; Tarantino & Mongiovì, 2001, 2002; Ridley *et al*., 2003). Particular attention was paid to the relation between the changes in suction and soil properties in terms of initial suction, degree of saturation and precompression stress. Changes in pore-size distribution at two stages of loading was also analysed by using the mercury intrusion technique to interpret qualitatively the different features observed in the mechanical tests.

2. Materials and methods

For this study, a loamy soil (173 g clay kg^{-1}, 777 g silt kg^{-1}, 50 g sand kg^{-1}) from the INRA experimental farm located at Mons in Northern France was used. The soil had a liquid limit of 0.29 g g^{-1}, a plasticity index of 0.06 g g^{-1} and a solid density of 2.7 Mg m^{-3}. Air-dried soil was passed through 2 mm and 0.4 mm sieves and then stored with a 0.02 g g^{-1} water content.

2.1. Oedometer compression test with soil suction measurements

Matrix suction measurements

The matrix suction of soil specimens was measured using a tensiometer inserted through an opening hole in the base pedestal in a standard 70 mm diameter oedometer, as shown in Figure 1. The soil sample was placed inside the oedometer in contact to the tensiometer, then covered by a load cap to enable vertical loading by the piston. A neoprene membrane was fixed to cover the soil and cap to avoid any evaporation that could cause an increase of soil suction. The effect of membrane is examined first. As mentioned above, only when the pore-air pressure in the soil specimen was equal to zero (*i.e.* the atmosphere pressure) during compression, the measurement of pore-water pressure u_w measured with the tensiometer was equal to the matrix suction of the soil s. Consequently, an air pocket of 15 mm high was provided at the top of the soil sample (Figure 1).

The tensiometer used (Figure 2) is of Imperial College type (Ridley & Burland, 1993, 1996). This type of tensiometer has been used successfully to perform suction measurements under laboratory conditions (Dineen & Burland, 1995; Ridley & Burland, 1996; Tarantino *et al*., 2000; Tarantino & Mongiovì, 2001, 2002; Ridley *et al*., 2003). It has provided excellent performance in terms of accuracy, measurement duration and operating tension range (0-1.5 MPa, Tarantino & Mongiovì, 2001). It was used by Cui *et al*. (2007) to monitor field suction changes. The tensiometer consists of a porous ceramic stone with a 1.5 MPa air entry value, a water reservoir 0.1 mm thick and a strain gauge attached to the diaphragm plate (Figure 2).

The presence of air in the water reservoir can cause cavitation of the tensiometer under a suction below the maximum working tension. This in turn makes it impossible for the tensiometer to measure suction. Therefore it is important to well saturate the tensiometer prior to use. The tensiometer was saturated in a saturation cell (80 mm in diameter and 70 mm high) as described in Mantho (2005) using a digital pressure-volume controller. After each measurement, the tensiometer had to be placed in the saturation cell and re-saturated at 2 MPa for 48 h.

A calibration stage of the tensiometer was also necessary after the saturation stage. The voltage of the tensiometer was recorded while the pressure was applied in steps using a digital pressure-volume controller which applied a positive pressure to the tensiometer with a precision of 1 kPa. The calibration curve obtained in the positive range was then extrapolated in the negative range. Tarantino & Mongiovì (2001) showed that the calibration curve is the same in the positive and negative ranges. This calibration stage was used also to estimate the tensiometer accuracy: it depended on the previous saturation stage and varied from 1 kPa to 6.9 kPa with a mean of 2.8 kPa.

Testing program

Soil samples were prepared by compacting soil fragments < 2mm or < 0.4 mm which were re-wetted at different initial water content w_{i} =0.125, 0.143, 0.16, 0.198 and 0.25 g g^{-1} water content by spraying. The same mass of dry soil was used for all samples (103.62 ± 0.05 g). Initial compaction was carried out directly in an oedometer to prepare soil samples. The final dimensions of the soil samples were: diameter 70 mm; height 24 mm; corresponding to a bulk dry density of 1.1 Mg m^{-3}.

After producing the soil sample, vertical stresses of 10, 20, 50, 100, 200, 400 and 800 kPa were applied step by step using a controlled pneumatic system. Unloading was carried out following the same stress steps until 50 kPa. Tests were performed under undrained conditions for water. The vertical displacement was recorded using two transducers (accuracy of 0.01 mm) installed symmetrically (Figure 1). The final water content was determined by oven-drying at 105°C for 24 h. These measurements enabled the determination of bulk density, void ratio and saturation degree of the soil samples. During loading and unloading, suction changes were continuously monitored by the tensiometer installed on the oedometer. Three compression tests were performed for each initial water content conditions.

2.2. Pore-size distribution measurements

Mercury intrusion porosimetry

The pore-size distribution was studied using the mercury intrusion technique. Mercury, a non-wetting liquid, was pushed into an air-dried soil sample under pressure (Fiès, 1984; Bruand & Prost, 1987). The relationship between the equivalent pore diameter (D_{eq}, in µm) and the suction (s, in kPa) was obtained from the Jurin-Laplace law:

$$D_{\mathrm{eq}} = 4\gamma(cos\,\alpha)/s \qquad (1)$$

where γ is the interfacial tension between air and mercury (0.484 N m^{-1}), α is the contact angle between the soil and the mercury (130° from Good, 1984)**.** The pressure range was from 4 to 200 000 kPa and the corresponding pore diameter was from 360 to 0.006 µm. Soil volumes of about 3 cm^3 were used for this study. They were oven-dried at 105°C for 24 h prior to taking the measurements (Richard *et al*., 2001).

Testing program

Soil samples for pore-size distribution measurements were prepared by compaction by using the same procedure as in the previous mechanical tests: two samples with soil sieved at 2 mm and two samples with soil sieved at 0.4 mm. The bulk dry density of the four samples was 1.1 Mg m^{-3} and their water content was 0.16 g g^{-1}. One sample of each sieve size (2 mm or 0.4 mm) was loaded in the oedometer by steps of 10, 20 kPa, whereas the two others were loaded in steps of 10, 20, 50, 100, 200, 400 kPa. All the samples were unloaded in one step and then air-dried to determine pore-size distribution. Two clods of about 3 g for each sample were measured for this study to ensure repetition.

3. Results

3.1. Evaluation of the soil suction measurement procedure

It was necessary to ensure the quality of soil suction measurements by taking precaution relating to possible evaporation and the rate of equilibrium. The variation of suction was measured in a soil sample within the oedometer over a 48 h period under a vertical stress of 200 kPa. A suction increase of about 1 kPa was measured, showing that the anti-evaporation system using a neoprene membrane was satisfactory. As the duration of a complete compression test was about 5 h, the effect of water evaporation on suction variation could be neglected. Figure 3 presents the variation of the pore-water pressure (u_w) under a vertical stress of 800 kPa. It was observed that once a vertical stress was applied, the pore-water pressure immediately increased (positive value) and then decreased after about five minutes. This study focused on equilibrium stage. As mentioned before, any air pressure u_a built up during compression could affect u_w. This problem was overcome by letting the expelled air reach the air pocket (Figure 1). Moreover, it was necessary to ensure the equilibrium in terms of soil volume changes and water transfer within the soil. In the present work, periods of 40 min for each load step and 5 min for each unload step were used to reach equilibrium for suction and strain measurements.

3.2. Soil suction changes during loading

Figures 4a-f present the variations of soil suction under loading for different initial soil suctions and different aggregate fractions (< 2 mm or 0.4 mm) after equilibrium. As regard to the standard deviation measured for different initial conditions, suction change characteristics are as following. Suction slightly increased for low vertical stresses and remains constant up to a stress of 800 kPa at an initial water content w_i= 0.125 g g^{-1} (initial fragments less than 2 mm, Figures 4a). Suction remained constant for soil samples with a water content 0.143 g g^{-1} (initial fragments less than 2 mm, Figures 4b). For soil samples with a water content higher than 0.16 g g^{-1}, suction initially remained constant up to a stress threshold value (σ_t) after which it decreased (Figures 4c-f). We determined σ_t by comparing the variation in the suction value between two successive applied stresses and the standard error of the second stress (vertical bars). If this difference was greater than the standard error, we assumed that the first stress corresponded to σ_t. The stress threshold (σ_t) and corresponding suction (s_t) are presented on Table 1 for all the samples. It can be observed that σ_t varied from 50 to 400 kPa. For the initial size of soil fragments < 2mm σ_t decreased with the initial water content (or increased with the initial suction) and σ_t for the initial size of soil fragments < 0.4 mm was lower than those of <2 mm for an initial water content of 0.16 g g^{-1} (Figures 4c and 4f).

We calculated the maximum equivalent diameter D_{eq}^* giving by the Jurin-Laplace law (Eq. 1, γ= 72.75×10^{-3} N m, cosα= 1) corresponding to the threshold σ_t for all initial conditions to examine the relation between the change in soil suction with vertical stress to the change in pore size distribution measured by mercury porosity. The maximum equivalent diameter D_{eq}^* varied from 2 µm for an suction s_i =14.6 kPa to 22.4 µm for s_i = 13 kPa (Table 2).

3.3. Compression behaviour on loading

In the following, changes in void ratio and pore size under compression were examined in order to better understand soil suction and threshold stress variations in relation to macroscopic soil characteristics such as precompression stress and degree of saturation.

Void ratio change

The variation of void ratio versus the logarithm of vertical stress is illustrated in Figure 5 for one soil sample. The curve shows an overconsolidated behaviour of the soil, i.e. a slight decrease in void ratio until precompression stress (σ_p), followed by a considerable decrease in void ratio. Precompression stress was determined graphically (Figure 5) by using the standard method for geotechnical engineering [AFNOR, 1997; Bardet, 1997]. The first straight line with slope κ; which is assumed to be equal to slope κ' defined on the unloading curve, is drawn across the initial point (σ_v = 10kPa); (2) the second straight line with slope λ is drawn across the point that has a maximum value of $\Delta e/\Delta \ln\sigma_v$ (σ_v = 100 kPa for these samples); (3)

the intersection of the two lines gives the precompression stress. The same calculation procedure was applied to other compression curves under different initial conditions. Table 1 gives all the σ_p values with standard errors. It can be observed that precompression stress decreased with water content, from 33 kPa to 16 kPa, and did not depend on initial fragment size. These measurements were consistent with those in the literature, showing similar effects of soil water content on the precompression stress (Alexandrou & Earl, 1998; Horn & Fleige, 2003; Imhoff *et al.*, 2004).

Change in saturation degree

Figure 6 shows the compression curve of the degree of soil saturation versus the logarithm of vertical stress for the same soil sample presented on Figure 6. We obtained a saturation degree value corresponding to the observed stress threshold value (S_r^t). The S_r^t values varied from 66 to 73% with initial soil fragments less than 2 mm (Table 1). A value of 43% was found for the samples of 0.4 mm sieve size. In addition, we observed that the final water content w_f was equal to 0.207 g g^{-1} for initial water content w_i of 0.25 g g^{-1} although the mechanical test was performed under undrained condition (Table 1). This difference was related to water loss from the sample after reaching the saturation state ($S_r = 100\%$). This quantity was found in the edges of the oedometer cell. As the value of σ_t in this test was equal to 50 kPa and the corresponding S_r value was 73%, a constant water content of 0.25 g g^{-1} could be considered below σ_t.

Larson & Gupta (1980) investigated the soil saturation degree at the transition point beyond which suction increased. They found that the transition occurred at the same soil saturation degree for the samples at different initial suctions. They established a relation between this transition saturation degree S_r^{t*} and the soil texture based on the results from 54 soils. The relation is as followed for $CC < 33\%$:

$$S_r^{t^*} = 0.364 + 0.00659CC \qquad (2)$$

where CC is the clay content (%);

Table 1 presents the transition saturation degree S_r^{t*} calculated for the different tests. Table 1 shows that the threshold stress corresponds to a transition saturation degree S_r^{t*} of about 70% for the samples of 2 mm sieve size and 43 % for the samples of < 0.4mm.

Change in soil pore-size distribution

Samples of different sieve sizes were loaded to 20 kPa and to 400 kPa. Both stresses compact the soil at respectively 1.2 Mg m^{-3} under 20 kPa and 1.65 Mgm^{-3} under 400 kPa in the oedometer cell. Table 2 shows the measurements performed on clods of 3g which were sampled from the oedometer compacted samples and oven dried. The dry bulk densities of clods were about 1.3 Mg m^{-3} for samples compacted at 20 kPa and 1.75 Mgm^{-3} at 400 kPa. Figure 8 shows the differences in pore volume per mass unit of the oven dried soil as a function of the equivalent pore diameter. The pore volumes were calculated with two repetitions (two clods taken from the same sample). The standard error was ± 0.001 maximum. Bruand & Prost (1987) proposed identifying three classes of pores (A, B, and C) to analyse the curves obtained by using mercury porosimetry. The threshold between pore class A and B is 40 µm, and 0.05 µm between B and C. The results (Table 2) obtained in the present work show that we have almost the same total volumes of pores under 20 kPa and 400 kPa (about 0.40 and 0.20 cm^3 g^{-1}) for the two types of sample (2 mm and 0.4 mm). At 20 kPa, the majority of pores belonged to class A for the sample of 2 mm and to class B for the sample of 0.4 mm. Furthermore, the pores of class C changed slightly for the two sample types. When loading from 20 to 400 kPa, the pores of class A decreased significantly for the two sample

types and remained low for the soil of 0.4 mm sieve size (0.006 $cm^3\ g^{-1}$). At 400 kPa, the pores of class B decreased significantly for the 0.4 mm sample but not for that of 2 mm.
We compared the porosity measurement of 0.4 mm sieve size at a vertical stress of 400 kPa in comparison to soil samples of 2 mm sieve size. Figure 7 presents the difference in pore volume distribution between samples at 1.2 and 1.65 Mg m^{-3} for both size aggregate fractions. Figure 7 shows that there are few new small pores for clods of 0.4 mm sieve size at a vertical stress of 400 kPa in comparison to soil samples of 2 mm sieve size for which there were far more new small pores. Table 2 presents the volume of pores of mean size smaller than the D_{eq}^* which is 6 µm for $w_i = 0.16$ g g^{-1}. The volume of new pores smaller that 6 µm is higher for clods of 0.4 mm sieve size in comparison to soil of 2 mm sieve size.

4. Discussion

Our study focussed on the equilibrium stage for soil suction because models for soil compaction usually consider stress and strain at equilibrium (Défossez and Richard, 2002). But wheeling in cultivated soils involves with a short loading dynamics. Different authors investigated the time response of soil suction in relation to short loading or cyclic loading (Peng *et al.*, 2004 ; Krümmelbein *et al.*, 2008). Our observations that the pore-water pressure immediately increased (positive value) and then decreased (Figure 3) confirmed the results reported by Peng *et al*. (2004) and Tombolato *et al.* (2004) who reported measurement of soil suction *in situ* during compression. The dynamics of the tensiometer response depends on the tensiometer itself and on the soil, especially its unsaturated hydraulic conductivity (Selker *et al.*, 1992, Hayashi *et al,* 1997; Timlin & Pachepsky, 1998). In term of intensity, the immediate pore water pressure should equal the external applied pressure in saturated conditions. In contrast, this transmission in stress is much less in unsaturated conditions as illustrated in Figure 3, the transmission was 160 kPa for an applied stress of 800 kPa.

When modelling soil compaction due to the passage of agricultural vehicles, it has been generally assumed that total stress can be used and that matrix suction remains constant (or constant water content) under the undrained conditions generally assumed in regards to the short loading time (< 0.1 s). Our results show that for a static compression under undrained conditions, there is a domain of stress where this assumption holds. This domain is delimited by a threshold stress (σ_t) which depends on the initial soil suction: the higher the initial suction, the higher the stress threshold. These results are in agreement with those obtained by Larson & Gupta (1980), Wulfsohn *et al.* (1998), da Veiga *et al.* (2007) but differ from those obtained by Tarantino & Tombola (2005). Larson & Gupta (1980) measured the change in matrix suction during uniaxial compressions of 54 soils at different initial suctions ranging from 5 to 60 kPa. They observed that under loading the matrix suction increased to a certain value and then decreased. The maximum increase in soil suction (20 kPa) was obtained under low initial suctions of 20 and 40 kPa. Our results show a similar characteristic for an initial soil suction of 146 kPa, with a maximum increase of about 10 kPa. Wulfsohn *et al.* (1998) studied the influence of matrix suction on soil strength by performing triaxial tests on a sandy clay loam at an initial bulk density of 1.2 Mg m^{-3} and an initial suction of 50 kPa. The applied confining pressure varied from 1.5 to 250 kPa. They observed that when the confining pressure was lower than 50 kPa, the variation in matrix suction was less than 8 kPa. The suction decreased significantly in the case of higher confining pressures. Da Veiga *et al.* (2007) investigated the effect of long-term tillage (no tilled, chisel ploughed, conventional tillage) on the soil suction change under compression for clay soils (clay fraction up to 700 g kg^{-1}). The matrix suction first increased and after decreased if stresses greater for the three testaments but the first increase was less pronounced for no-till systems. Tarantino & Tombola (2005) reported measurements on clay soil (clay fraction 800 g kg^{-1}) at different initial bulk density ranging from 1.05 to 1.3 Mg m^{-3} for which soil suction increased systematically during compression. It appears therefore from different studies that a transition point below which the assumption of constant suction holds can be observed. Questions remain regarding the stress threshold value σ_t with respect to the stress usually applied by vehicle in agriculture (< 400 kPa) and regarding the factors affecting σ_t.

We investigated the relation between the soil saturation and the transition point beyond which suction increased according to Larson & Gupta (1980) who found that the transition occurred at the same soil saturation degree for samples initially at different suctions. By applying the Larson & Gupta's relation to our soil (Eq. 2), we obtained a roughly constant transition saturation degree S_r^{t*} of 70% for samples initially at different suctions for aggregate fraction <2mm (Table 1). This confirms that the saturation degree is a factor that affects the threshold stress. But the transition saturation degree S_r^{t*} was significantly different for the aggregate fraction <0.4 mm (S_r^{t*} = 43%) so that soil structure should also be taken into account for predicting threshold stress. Furthermore the results reported by Tarantino & Tombola (2005) on clay soil (clay fraction 800 g kg^{-1}) suggest that the relation proposed by Larson & Gupta (1980) may be not valid for soils with a very high clay content..

Peng *et al.* (2004) proposed correlating soil suction variations during compression with precompression stress (σ_p), as σ_p depends on soil texture, soil structure and soil suction. Table 1 shows that for w = 0.16, 0.198 and 0.25 g g^{-1}, threshold stress σ_t was respectively 400, 200 and 50 kPa, much higher than the corresponding precompression stress (34, 21, 16 kPa). This shows that the threshold stress σ_t would be lower with low precompression stress, but the domain of constant soil suction was larger than that delimited by the precompression stress.

The interpretation of the changes in soil structure accompanied by changes in soil suction during compression can be made qualitatively at pore scale. Intuitively the compaction at constant water content can be thought at first sight as followed: a global decrease in pore space should cause a decrease in soil suction, *i.e.* the soil water volume remains constant while pore size decreases and pores disappear under compression. However this view does not consider that the change in pore size is not homogeneous for all pore size under compression.

Our results obtained by mercury porosimetry showed that mechanical compression induced a decrease in large pore volume and an increase in small pore volume with a limit between disappearance and creation for pore size of few microns. The pore size distribution did not change in a uniform fashion. Our observations are consistent with observations showing that compaction may decrease large pores (> 10 μm) and increase small pores (0.1 - 10 μm) in soils of varying texture in the range of mechanical stress applied in agriculture (< 400 kPa) (Bruand & Cousin, 1995; Richard *et al.*, 2001; Tarawally *et al.*, 2004; Kutílek *et al.*, 2006). Our hypothesis is that the domain of constant suction results from competition between the redistribution of soil water in small pores created by compression that tends to increase soil suction and a global decrease in pore space that tends to decrease soil suction. This assumption can be examined by comparing qualitatively the change in soil suction with vertical stress observed for samples at an initial suction s_i of 47 kPa for both aggregate fractions (<2 mm and 0.4 mm) (Figure 5c and 5f) to the change in pore size distribution measured by mercury porosity for clods sampled in compacted volumes obtained after vertical stresses of 20 kPa and 400 kPa for both aggregate fractions at the same initial suction (47 kPa) and oven-dried after compaction.. There are few new small pores for clods of 0.4 mm sieve size at a vertical stress of 400 kPa in comparison to soil samples of 2 mm sieve size. This feature could explain the difference in the values of stress threshold σ_t = 400 kPa for 2 mm sieve size and σ_t = 100 kPa for 0.4 mm sieve size for soil at an initial suction of 47 kPa. At an initial suction of 47 kPa, one can assume that water is essentially located in pores with a maximum equivalent diameter D_{eq}^* of about 6 μm. This pore size falls within the range of pore size at which creation of new pores was observed. Thus, soil suction is assumed to increase or decrease depending on the evolution of maximum equivalent diameter D_{eq}^* with mechanical stress level as schematized in Figure 8: at a vertical stress of 400 kPa, suction remains constant for 2 mm sieve size sample because there is still enough new pores that could contain the water coming from the disappeared macropores so that the maximum equivalent diameter D_{eq}^* remains constant whereas suction decreases for 0.4 mm sieve size sample because mechanical loading did not create enough new pores anymore. The decrease of stress threshold σ_{t} with decreasing initial soil suction could also be interpreted in terms of water redistribution at pore scale. A soil suction of 13 kPa corresponds to an equivalent pore diameter of about 22 µm (Table 1). At this suction level, the creation of more small pores by loading could be expected (not measured), but their volume would not be sufficient to contain the soil water from the destroyed pores, thus soil suction decreases (Figure 4e). On the contrary, at a high soil suction of 146 kPa, new small pores are assumed to lead to a redistribution of water to smaller pores that tend to increase soil suction. This agrees with the increase in soil suction at low vertical stresses observed for high initial soil suction (Figure 4a).

This analysis of the changes in soil suction during compression in relation to change at pore scale is restricted to qualitative considerations. Indeed, quantitative analysis is limited by methods used for sampling and drying in this study. As the volume of clods used in mercury porosimetry is small (mm^3) in comparison to volume of soil in the oedometer cell (cm^3), sampling for mercury porosimetry is expected to represent partially the soil structure of oedometer samples: the crack and macropores may be underestimated by mercury porosimetry. Secondly the technique used to dry the soil before porosimetry induces unavoidable shrinkage which can be limited by freeze-drying technique (Delage *et al.*, 1996). Both sampling and drying can explain discrepancies in dry bulk density of clods in comparison to initial compacted volume as reported in Table 2. Further investigation in the relation between macroscopic threshold σ_{t} and pore size distribution in relation to soil suction involves with the difficult problem of quantifying the change in pore space due to compaction in relation to retention properties (Pagliai *et al.*, 2003; Hajnos *et al.*, 2006; Schäffer *et al.*, 2007).

5. Conclusion

Variations of soil suction under static compression were investigated using an oedometer with soil suction measurements. For initial suction higher than 20 kPa, matrix suction remained quasi constant under a stress threshold σ_{t} which increased with increasing initial soil suction and with increasing sieve size. For initial suction higher than 20 kPa, the values of stress threshold σ_{t} fell within the range of mechanical vertical stress generally exerted by agriculture machines (< 400 kPa). This corroborates the assumption of constant suction during deformation usually adopted in modelling soil compaction due to traffic but questions its validity for soils close to saturation.

The suction variations during loading were qualitatively analysed at pore scale using pore-size distribution measured by mercury porosimetry. Loading deforms the pores; large pores deform, decrease in size and create new small pores. If the water saturation degree is low (case of low water content and high suction), the volume of the smaller pores created is sufficient to balance the water flow caused by the destruction of other pores, thus soil suction tends to increase or remains constant. This is the case for $\sigma < \sigma_{\mathrm{t}}$. For higher initial saturation degree (case of higher water content or higher vertical stress), the new small pores no longer compensate the loss of larger pores and any further loading leads to a decrease in suction. This is the case for $\sigma > \sigma_{\mathrm{t}}$. The aggregate size as shown in this study and the clay content as shown by Larson & Gupta (1980) change the stress threshold σ_{t} probably because of different evolution of pore size distribution as the soil deforms. Further measurements on aggregate fractions higher than 2 mm should be performed to provide a closer study of this effect of soil structure on stress threshold σ_{t}, which is an important element in soil modelling.

Acknowledgements

We thank Mr. F. Bornet (UR1158, INRA, France) and Mr. E. Delaure (CERMES, ENPC, France) for their assistance in the development of the mechanical set-up, and to Mrs. I. Cousin and Mr. O. Josière (UR0272 Science du Sol, Orléans, INRA, France) for pore-size distribution measurements. The authors thank the French GESSOL2 Program of the Ministry of the Environment and the ADD Program of the National Research Agency for providing their support to the DST project (Soil degradation due to compaction) of which this work is a part.

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Table 1 Results of oedometer compression tests with measurements of soil suction

Initial water content w_i /g g^{-1}	Initial soil suction s_i/kPa	Initial size of soil fragments /mm	Final water content w_f /g g^{-1}	Stress threshold value σ_t /kPa	Suction at threshold stress s_t /kPa	Precompression pressure σ_p /kPa	Saturation ratio at threshold stress $S_\mathrm{r}^{\mathrm{t}*}$ /%	Equivalent diameter D_eq^{*} /µm$^\mathrm{a}$
0.125	146	<2	0.125	—	—	33±2	—	2.0
0.143	66	< 2	0.143	—	—	24±1	—	4.4
0.160	47	<2	0.159	400	42±4	34±6	66±5	6.2
0.198	19	<2	0.197	200	22±1	21±2	71±5	15.3
0.250	13	<2	0.207	50	13±2	16±3	73±9	22.4
0.160	53	<0.4	0.160	100	52±1	35±3	43±1	6.2

[a] calculated with the average value of initial soil suction.

Standard deviation was calculated from three replicates

Table 2 Pore volume measurements performed on clods taken from soil samples compacted at two vertical stresses.

Sieve size /mm	Applied vertical stress /kPa	Dry bulk density /g cm^{-3}	Void ratio e /cm^3 cm^{-3}	Pore volume[a] /cm^3 g^{-1}	Volume of pores A[a] /cm^3 g^{-1}	Volume of pores B[a] /cm^3 g^{-1}	Volume of pores C[a] /cm^3 g^{-1}	Volume of pores < D_{eq}* /cm^3 g^{-1}
2	400	1.68	0.60	0.188	0.011	0.162	0.015	0.149
0.4	400	1.65	0.64	0.207	0.006	0.182	0.019	0.192
2	20	1.20	1.25	0.407	0.206	0.190	0.011	0.127
0.4	20	1.18	1.28	0.401	0.060	0.323	0.017	0.127

[a] average values for two repetitions with maximum standard error of 0.001 cm^3 g^{-1}

Figure captions

Figure 1: Oedometer equipped with a tensiometer for suction monitoring. Schematic layout of the neoprene membrane covering the oedometer cell: an air pocket of 15 mm high is provided between the membrane and the cell.

Figure 2: The tensiometer.

Figure 3: Pore-water pressure u_w versus time under a vertical stress of 800 kPa applied at the 14th minute (soil sample with initial fragments < 2 mm, 0.16 g g^{-1} water content and 1.1 Mg m^{-3} dry bulk density).

Figure 4: Change in matrix suction with vertical stress as a function of initial fragment size and water content of soil samples. Each point corresponds to soil suction measured after equilibrium of about 40 min with applying a constant vertical stress. The points indicate the average values from three tests; the vertical bars indicate the standard errors. An initial suction at 2 kPa vertical stress was considered because of the logarithmic scale.

Figure 5: Void ratio (e) versus vertical stress for a soil sample with initial fragments less than 2 mm, an initial water content of 0.16 g g^{-1} and an initial dry bulk density of 1.1 Mg m^{-3}. The precompression stress, σ_p, was determined by the intersection of two straight lines.

Figure 6: Saturation degree versus vertical stress for the soil sample at an initial dry bulk density of 1.1 Mg m^{-3} for initial water contents of 0.16 g g^{-1} (a) and 0.25 g g^{-1} (b). The stress threshold and the corresponding saturation rate were estimated respectively at σ_t= 400 kPa and S_r^t= 66 % for w_i=0.16 g $g^{-1}$and σ_t= 50 kPa and S_r^t= 73 % for w_i=0.25 g g^{-1}.

Figure 7: Differences in pore volume distribution between samples at 1.2 and 1.65 Mg m^{-3} of dry bulk densities as a function of pore equivalent diameter for the soil samples of 2 mm sieve size (open square) and of 0.4 mm sieve size (black square). Maximum standard error was 0.001 cm^3 g^{-1}.

Figure 8: Schema of mechanisms proposed to explain suction variation under compression at low stress (< σ_t). Compaction induces a decrease in volume of large pore, but this decrease can be compensated by an increase in small pore volume so that water can hold in smaller pores under compression leading to a decrease in the equivalent diameter and an increase in the suction.

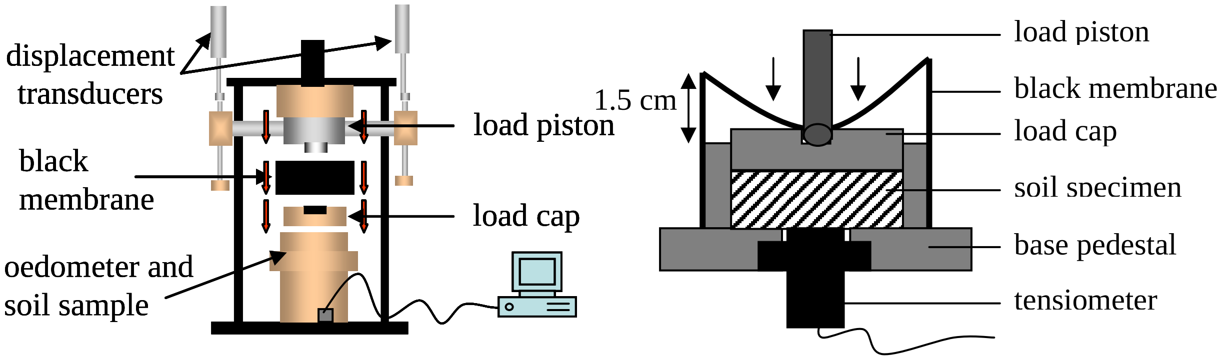

displacement transducers
black membrane
oedometer and soil sample
load piston
load cap
1.5 cm
load piston
black membrane
load cap
soil specimen
base pedestal
tensiometer

Figure 1

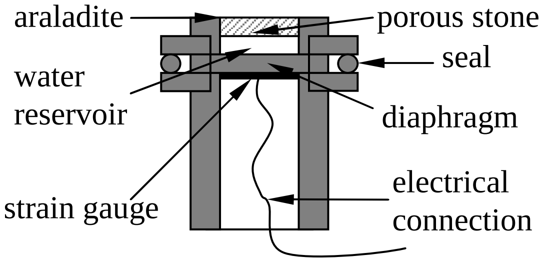

araladite
porous stone
seal
water
reservoir
diaphragm
electrical
connection
strain gauge

Figure 2

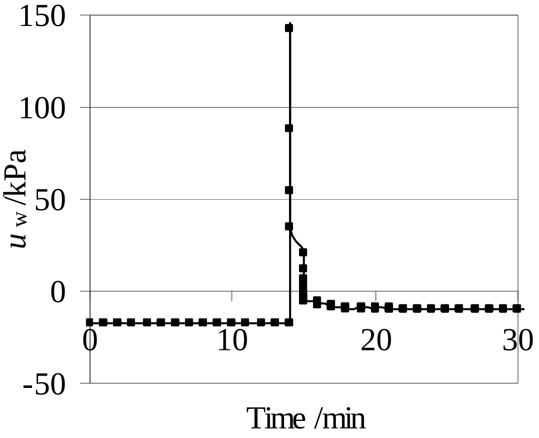
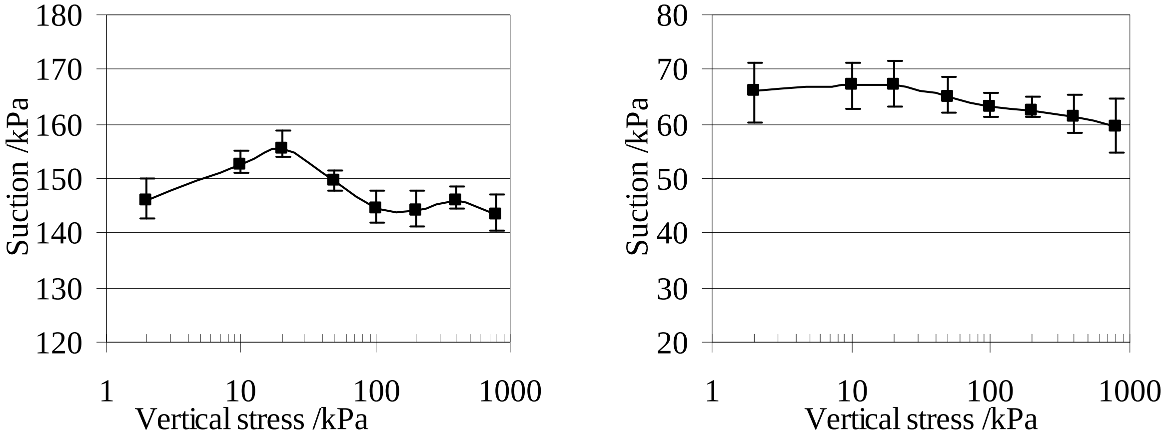
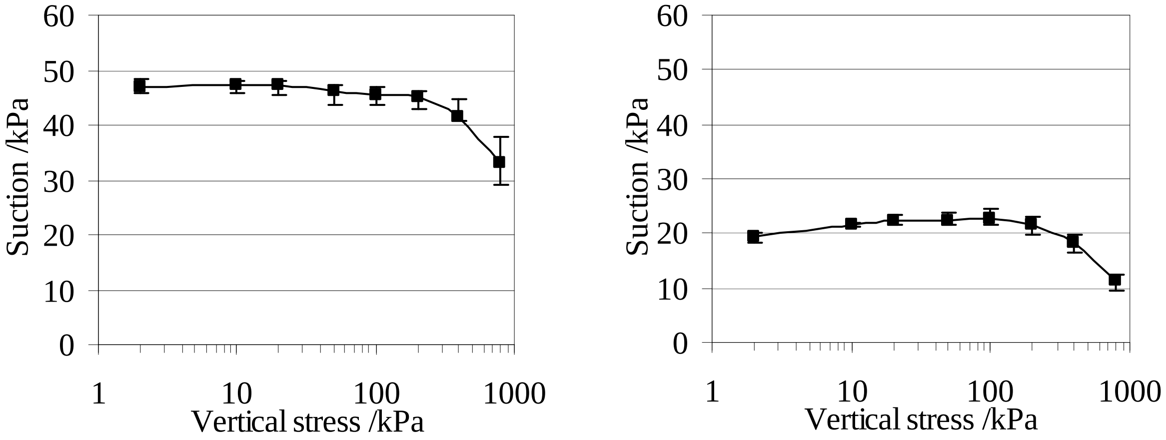


Figure 3:



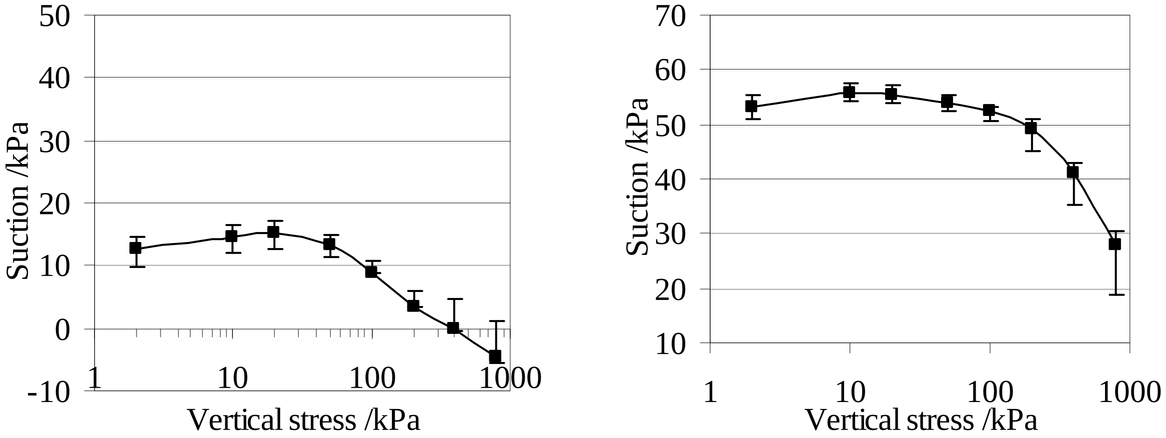
(a) fragments < 2 mm, $w_i = 0.125$ g g^{-1}

(b) fragments < 2 mm, $w_i = 0.143$ g g^{-1}



(c) fragments < 2 mm, $w_i = 0.160$ g g^{-1}

(d) fragments < 2 mm, $w_i = 0.198$ g g^{-1}



(e) fragments < 2 mm, $w_i = 0.250$ g g^{-1}

(f) fragments < 0.4 mm, $w_i = 0.160$ g g^{-1}

Figure 4:

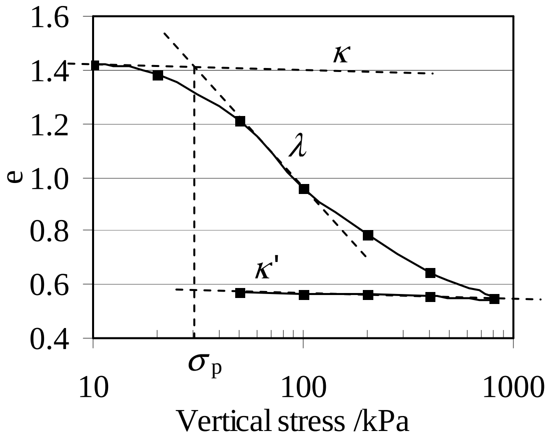

1.6
1.4
1.2
1.0
0.8
0.6
0.4
e
κ
λ
κ'
σ_p
10
100
1000
Vertical stress /kPa

Figure 5

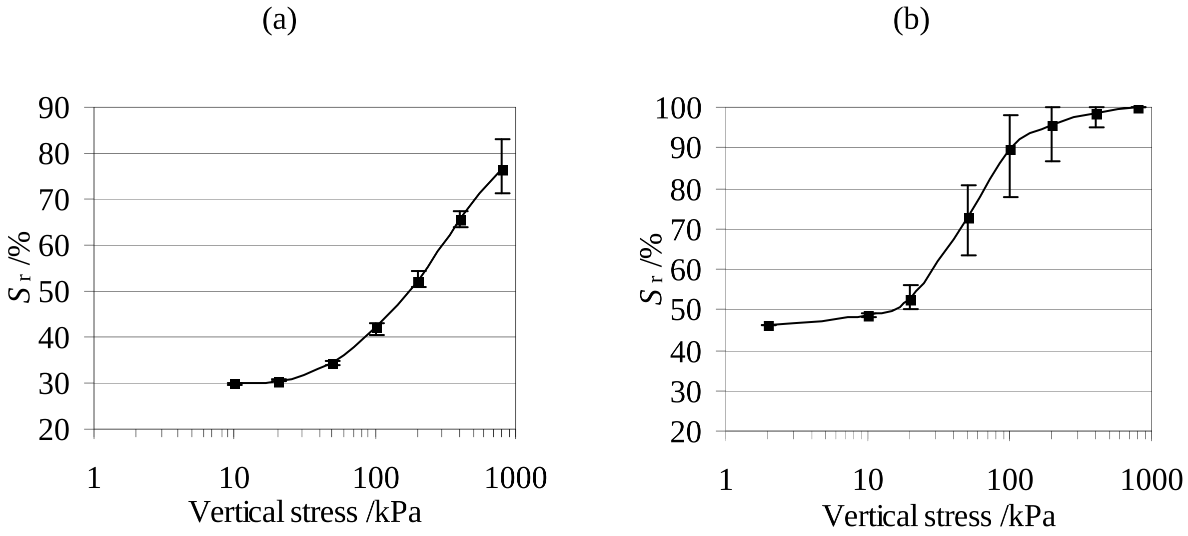

(a)
(b)
90
80
70
60
50
40
30
20
S_r /%
1
10
100
1000
Vertical stress /kPa
100
90
80
70
60
50
40
30
20
S_r /%
1
10
100
1000
Vertical stress /kPa

Figure 6

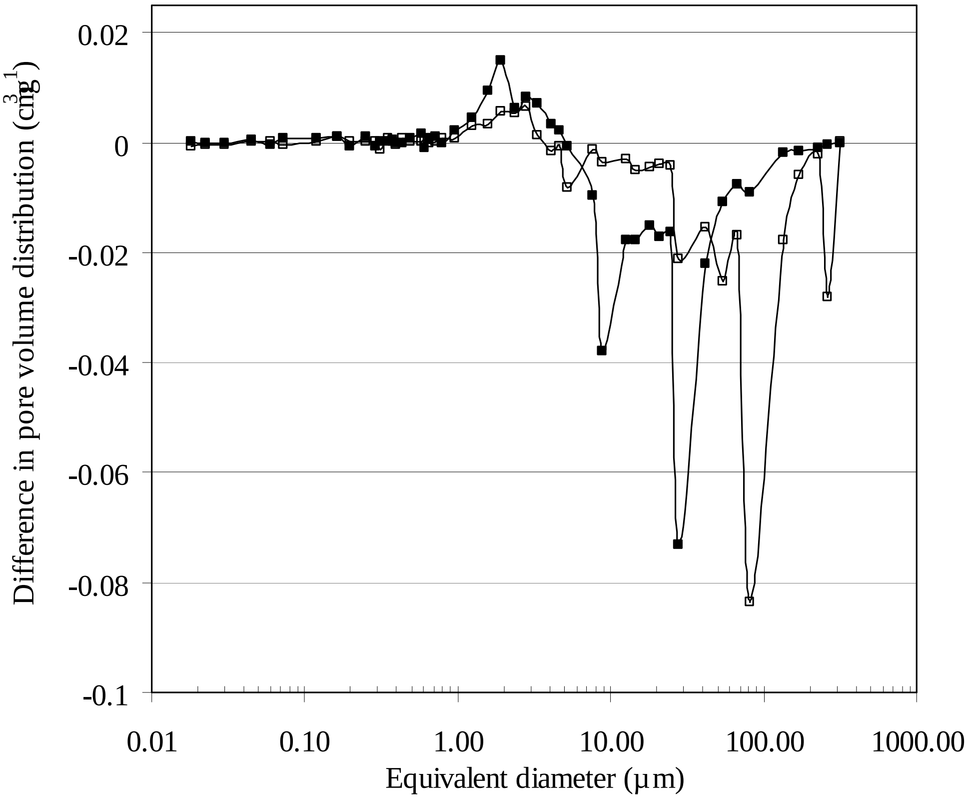

0.02
0
-0.02
-0.04
-0.06
-0.08
-0.1
Difference in pore volume distribution (cm^{3}g^{-1})
0.01
0.10
1.00
10.00
100.00
1000.00
Equivalent diameter (µm)

Figure 7

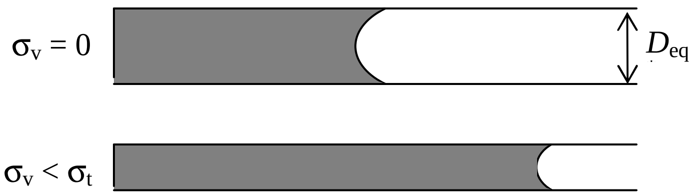


Figure 8