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Soil-Water Retention Curve Measured on Differently Sized Soil Core Samples

Diploma Thesis

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Declaration

I certify that I prepared the Diploma Thesis on “Soil-Water Retention Curve measured on differently sized soil core samples” by myself and I used only the literature sources which I quote and mention in the attached bibliography.

In Prague 13th April 2012

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Ayele Teressa

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Summary

The study was conducted to evaluate the difference in soil water retention curve data of a homogeneous porous material determined on the basis of the two most commonly used soil core samples: 100 cm^3 and 250 cm^3. The sample was packed silica sand with commercial name ST 56 from Střeleč area and prepared for sport pitch surface cover by Sklopísek Střeleč, a.s., Czech Republic. The sand was packed into the rings according to its average bulk density layer by layer in order to get uniform distribution through the soil column. Nine replicates were prepared for each core sample size, of which two replicates were taken randomly for the observation of saturated moisture distribution along the column, while the rest seven were exposed to suction in a sand tank for lower matric heads and to pressure in a pressure plate apparatus for higher matric heads. Gravimetric water content at saturation of each 10 mm layer of 50 mm high sample column was compared with that of the other layers and with average gravimetric water content of groups of samples for soil water retention curve determination. There was no significant difference either between the gravimetric water contents of individual or in comparison with the group of samples for retention curve determination. The suction/pressure heads 0, 5, 22, 40, 55, 70 and 2345 cm were applied to the latter samples and their volumetric water contents were calculated from their weights taken at equilibrium. The measured data were fit to several models developed for soil water retention curves using RETC computer program and the best fits were further analyzed. The analysis of both measured and fitted data showed that there is no significant difference in soil water retention curves over the range of applied matric heads for the homogeneous material studies between the two ring sizes.

Key Words: soil-water retention curve; water content; matric potential; sand tank; pressure plate.

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1. Introduction

Soil water retention curve and hydraulic conductivity are fundamental soil water properties that control storage and movement of water in the vadose zone. Water in this zone is the interest of agricultural production of crops and fodder, environmental and other related sciences and promotes a wide variety of physical, biological and chemical processes. Therefore, it is crucial to study water retained in the soil by soil suction.

Soil water retention curve is one of the basic soil water properties that relate soil suction with soil water content (Fredlund et al., 2001; Wraith and Or, 2002). The relationship between suction and water content is inverse and the curve is nonlinear with three stages, namely boundary effect (capillary saturation zone), transition (desaturation zone) and residual (residual saturation zone) stages (Fredlund, 2002).

Different soils have different soil water retention curves. This difference is primarily due to texture, structure and organic matter contents (Wraith and Or, 2002; Ali, 2010) and to some extent due to soil water chemistry (Dawson et al., 2008).

Soil water retention curve depends on the soil moisture history of the given soil. According to Ali (2010), among many other authors, soil moisture retention curves obtained by draining saturated soil/desorption and that by wetting up dry soil/sorption are not the same functions and the difference is due to soil water retention curve hysteresis.

Given that the other factors are remaining the same, soil water retention curve can be affected by temperature. Soil retains more water under lower temperature than under higher due to dependence of water surface tension on temperature (Shukla and Lal, 2004).

Soil water retention curve, according to Rajkai et al. (2004), can be estimated from easily measurable and available soil properties, like texture, organic matter content, structure etc., but can be also measured directly either in laboratory or at field (Kutilek and Nielsen, 1994). Data for soil water retention curve (soil water content and suction) in the field conditions are measured using a combination of different methods but in the laboratory the pairs of moisture content and matric head values can be obtained from a single apparatus over typical range of application, using sand tank, pressure plate, pressure membrane etc.

Data obtained for the derivation of the curve from either field or laboratory measurements are, according to Khlosi et al. (2008), discrete, while the actual soil water retention curve is a continuous function. Hence, measured data have to be fitted to the best soil water retention curve models that have been developed by different scientists.

This thesis is about to evaluate the effect of core sample size on soil water retention curve for a homogenous porous material. Samples for the study were packed into two different core samplers (100 cm^3 and 250 cm^3 volume, each with 50mm height). The soil for the experiment was silica sand with commercial name ST 56 from the Střeleč area in East Bohemia and prepared for different uses by Sklopísek Střeleč, a.s., Czech Republic. The measured data were fitted to different models developed for soil water retention curves using RETC computer software programme and used to evaluate soil water retention curves for the two ring sizes.

2. Aims and Objectives

Objective

The aim of the thesis is to evaluate the difference in soil water retention curve data of a homogeneous porous material, determined on the basis of the two most commonly used soil sample sizes: 100 cm^3 and 250 cm^3, and the impact of the sizes of core samplers on soil water retention curves for this homogeneous porous material.

Hypothesis

There is no significant difference between soil water retention curves due to the sizes of core samplers for these volume ranges and a particular homogeneous material.

3. Literature Review

3.1 Soil water retention curve overview

Soil water retention curve is one of the basic soil water properties that relate matric potential and water content, commonly volumetric, θ (Hillel, 1998; Barber et al., 2001; Shukla and Lal, 2004). The functional relationship can be also between matric potential and either gravimetric water content (ω) or degree of saturation (S) (Fredlund, 2002; Vanapalli et al., 1998; Khanzode et al., 2000; Fredlund et al., 2001; Wraith and Or, 2002). Due to the fact that the curve is the characteristic of each soil, it is also known as soil-moisture (soil-water) characteristic curve (Shukla and Lal, 2004; Miyazaki, 2006). However, as the curve is not the sole function of a given soil but varies with temperature, pore water chemistry and pressure, it is something of a misnomer to say soil water characteristics curve (Dawson et al., 2008). Fredlund et al. (2001) suggested that out of the name which shows the relationship between soil water content and soil water energy which they listed like soil-water characteristics curve, soil-water characteristics, retention curve, moisture retention curve, soil moisture retention curve, water retention curve, soil water retention curve, moisture release curve, etc, soil-moisture characteristics curve is used for soil mechanics like civil engineering while those expressed with retention can be used for soil physics like agricultural and environmental sciences. They reasoned it that the term “characteristic” has been the most used in engineering and the word curve shows the behavior of the given soil while retention is related to the retention of water for plants. Hence, from here on wards, it is better to use the term soil water retention curve (SWRC) to show the relationship between soil suction and its corresponding amount of water in the soil.

The curve is usually plotted from volumetric water content of the soil arithmetically against matric potential frequently in logarithmic scale to accommodate the large range of suction, roughly from three to six orders of magnitude (Kutilek and Nielsen, 1994), see figure (3.1). Hence, the curve is called semi-logarithmic or pF curve (Fredlund et al., 2001; Goss and Ehlers, 2003).

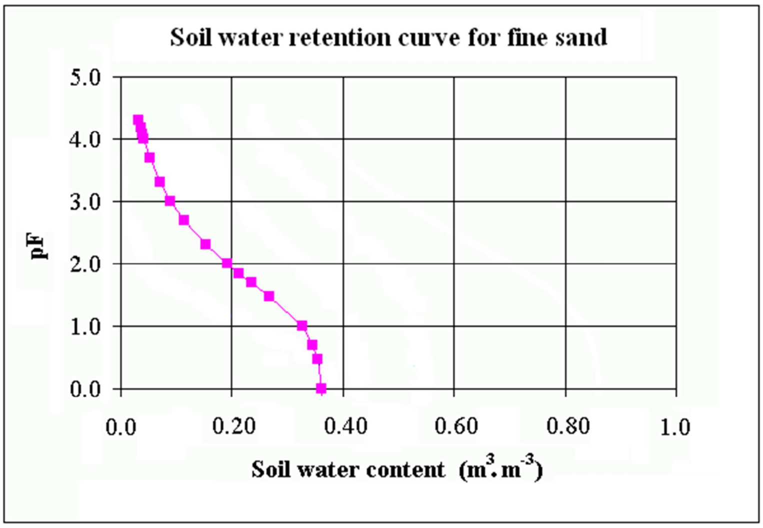


Fig. 3.1. pF Curve for Fine Sand (taken from: Karvonen, online)

Theoretically, soil has the minimum moisture content when soil is oven dried at 105^{0}c for 24 hours and maximum when fully saturated, hence it always has a none negative value while matric potential has a negative value but negative values cannot be plotted on a logarithmic scale; as a result matric potential is plotted as absolute and thus positive value (Fredlund et al., 2001).

3.2 Stages of Soil Water Retention Curve

Soil water retention curve is not linear (Behari, 2005). However, according to Miller et al. (2002) suction and water content are inversely related, but according to Wraith and Or (2002) it is relatively difficult to obtain it accurately.

Soil water Retention Curve has three identifiable stages (see fig. 3.2); namely: boundary effect, transition and residual (Fredlund et al., 2001). However, Fredlund et al. (1997) called these stages capillary saturation zone, desaturation zone and residual saturation zone respectively. According to Golder Associates (2006) the curve has two breaks, namely air entry and residual values that are used as the transition points between stages. Air entry value according to Fredlund (2002) separates the boundary effect stage from the transition stage while residual value separates transitional from residual stage.

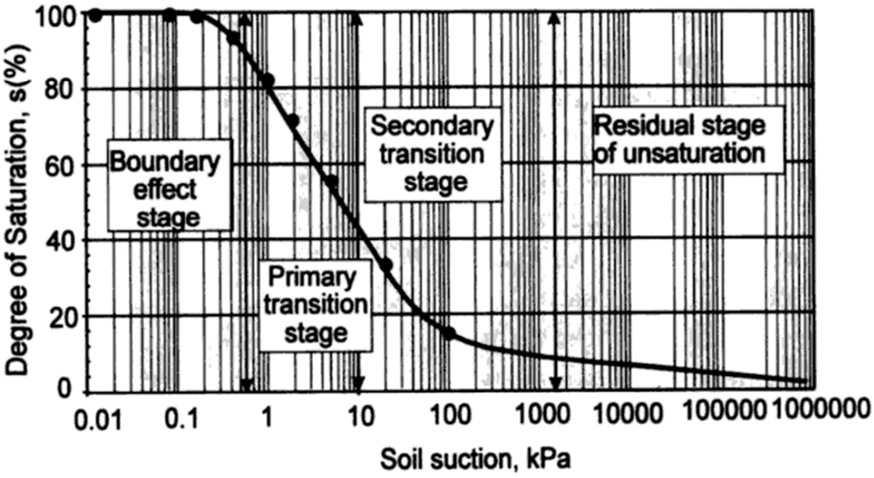


Fig. 3.2. Soil water retention curve showing the different stages of desaturation (from: Fredlund et al., p. 111)

N.B. The curve is from degree of saturation (%) on Y-axis and soil suction (kPa) on X-axis

When fully saturated soil is subjected to pressure, there will be no outflow from soil (sample) for slight suction according to Hillel (1998) until the critical value is surpassed at which the largest pores begin to lose water as it is displaced by air and this is the first or boundary effect stage. According to Shukla and lal (2004) the point at which soil moisture starts to decrease is known as the air entry point. Kutilek and Nielsen (1994) stated that the value of $d\theta/d\psi$ remains zero in this stage and soil hydraulic properties remain constant. They called the point at which water starts to flow out as air entry value and Hillel (1998) called the suction at this point air entry suction. He added that, fine or medium textured soils or poorly aggregated soil has high air entry suction while coarse textured and aggregated soil has the lower air entry suction. Moreover, according to Kutilek and Nielsen (1994), it is well defined and measured in coarse textured soils than in medium or fine textured soils.

After the critical, air entry value is exceeded through suction increment, the water content decreases and soil properties are no longer constant like in the boundary effect stage and hence the property of the soil becomes that of an unsaturated soil property function (Fredlund et al., 2001). According to Fredlund and Xing (1994) SWRC is the curve used to describe different unsaturated soil properties. The greatest interest is in the unsaturated part of the SWRC because suction change is generally related to change in water content of the soil due to water outflow (Peron et al. 2007). According to the capillary equation, ($\psi=2\gamma/r$, where, ψ is potential head, γ is the liquid-air surface tension and r is radius of tube) soon after the air entry value is reached, it is the relatively larger pores that lose water at first, and if suction keeps increasing, the smaller pores will follow (Hillel, 1998). According to Barber et al. (2001) beyond the air entry value SWRC is non-linear and the following stage next to air entry value is the transition or second stage. They explained that desaturation is in a liquid state in the lower part of SWRC under applied pressure and to keep increasing suction from air entry suction results in dropping the value of unsaturated hydraulic conductivities. However, at the drying end of SWRC according to Golder Associates (2006) increasing suction does not result in displacing a significant amount of water due to the association of water with smallest pores and adsorption in the form of a film on the particles and there are relatively small changes in water content. This stage is called the residual stage (Vanapalli et al., 1998) and desaturation in this part of the SWRC is due to both liquid and vapour phases; but according to Fredlund et al. (1996) it is through vapour at the latter part of the stage. Transition stage and residual stage are separated by residual point and according to van Genuchten (1980) from a practical point of view this point is sufficiently defined at large suction, at permanent wilting point (15,000 cm of suction head). However, permanent wilting point varies from plant to plant and stages of development for a given plant. The stage is associated with decreasing in thickness of the hydration envelopes adsorbed to soil-particle surfaces. The residual water content is also defined as the water content at which ($d\Theta/d\psi$)→0 of SWRC (Kutilek and Nielsen, 1994). However, according to van Genuchten et al. (1991) it extends to 10^6 kPa of suction.

3.3 Soil Water Retention Curve Hysteresis

Soil water retention curve can be obtained in two ways. According to Hillel (1998) and Ali (2010) it can be either by draining initially saturated soil (desorption method) or by wetting up initially dry soil to saturation (sorption method). Soil releases water during the desorption process and according to Mukherjee and Biswas (1994) the curve from this process is also known as water release curve. Soil moisture history, wetting or draining, affects the relationship between matric potential and soil moisture content and hence Soil-water retention curve from both conditions is not a unique function, see figure (3.3(a)) and they are different (Campbell, 1994; Hillel, 1998; Wraith and Or, 2002; Shukla and Lal, 2004). Soil water and matric potential are not uniquely related because they are dependent on the air-water interfaces and the nature of the surface film rather than the amount of water that exists in pores (Horton and Jury, 2004). They further explained that during sorption (wetting curve construction), pores are filled according to their size, small first and followed by bigger, but at intermediate values even though there is enough water in the soil, water-air interfaces can exist between particles and in small pores until the matric potential become zero. While during desorption (drying curve construction), bigger pores drain first, followed by the smaller; however, water is kept in the larger pores until the interconnected smaller pores can empty. During wetting of dry soil, air is entrapped even with sufficient water in soil while during drying saturated soil water is entrapped until the interconnected small pores lose their water. At any intermediate stage between saturation and air dryness, if the process of wetting or drying is reversed, the curve will follow a different course within the limits of sets of two boundary curves i.e. curves from wetting very dry soil to saturation from the lower and drying/draining the saturated soil (Rose et al., 1999) from the above. According to Fredlund (2002) two main curves from draining and wetting form a loop with an extreme bound and an infinitive number of loops fall within. Soil retains more water during draining than wetting at any reversal direction at the same matric potential (Horton and Jury, 2004). The phenomenon is called soil moisture retention curve hysteresis.

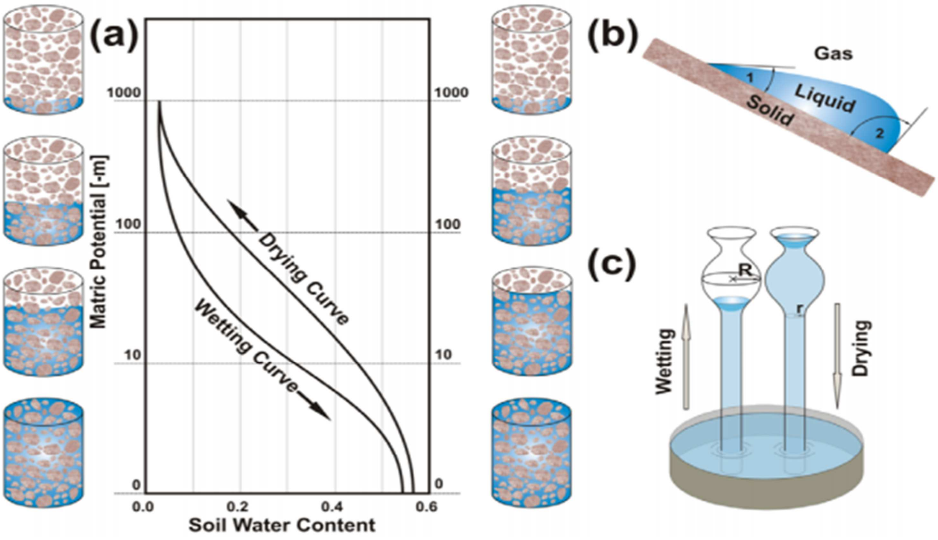


Fig. 3.3. (a) Conceptual sketch showing hysteresis of the SWRC. (b) The contact angle effect, and (c) the ink bottle effect as potential mechanisms for hysteresis. (from Tuller and Or, P. 14)

3.3.1 Factors/Reason for Soil Water Retention Curve Hysteresis

Soil moisture at a given matric potential is influenced by pore size distribution and properties of air-water-solid interfaces (Wraith and Or, 2002). Many soil pores are larger than their respective openings. These larger pores will remain full of water until the suction, Φ_m, surpasses Kr_s^{-1} (Rose et al, 1999). Where: K is constant and r_s is radius of the tube/effective pore (µm) and related as follows:

$$\Phi_m = 2\gamma / (\rho_w g r_s) = K r_s^{-1} \ldots\ldots\ldots 1$$

Where: Φ_m is Suction (Pa), γ is liquid-air surface tension (N/m), ρ_w is density of water (g/cm^3), g is gravity constant (m/s^2) and $(2\gamma/\rho_w g)$ take as K

Let us put the constant, K, aside and focus only on the effective radius of the soil during wetting and drying of the soil. Water in larger pores remains there until the suction overcomes Kr_s^{-1} i.e. $\Phi_m > Kr_s^{-1}$; where r_s is the effective radius of the small pores. In contrast, re-wetting of the soil can take place when the suction exceeds Kr_b^{-1} i.e. $\Phi_m > Kr_b^{-1}$; where, r_b is effective radius of the bigger pores. As suction and radius are inversely related, from this behaviour, we have more water in soil during draining than wetting at a given suction. This geometric non-uniformity of interconnected soil pores in shape and size is called the “ink-bottle” effect and it is one of the main causes of soil water retention curve hysteresis (Hillel, 1998; Wraith and Or, 2002).

Hysteresis is also caused by variation of contact angle between soil/water interfaces during wetting or draining (Shukla and Lal, 2004).

$$\Phi_m = 2\gamma\cos\beta / r = q\cos\beta \ldots\ldots\ldots 2$$

Where, β is the contact angle during drying or wetting.

Let us keep 2γ/r as a constant, q, and rearrange the formula as $\Phi_m = q\cos\beta$. Substitute β_d and β_w instead of β during draining and wetting respectively. β_d is presumed to be zero as contact angle may approach it during drying and $\cos 0^0$ is 1; while it is most likely non zero for wetting soil i.e. $\beta_w > 0$ and hence we have $\cos\beta_w<1$. For a given pore, the radius of curvature is less for retreating than advancing as the contact angle between the water meniscus and the pore walls is less when the meniscus is drying than when advancing (Scott, 2001; White, 2006). Hence, for a given soil moisture content, we have more suction during drying than wetting even though its value is negative (Shukla and Lal, 2004). In other words, for a given suction, Φ_m, r has to be greater for drying than wetting (Rose et al, 1999). Contact angle hysteresis can occur; wetting i.e. $\beta_w > 0$, due to surface roughness and or surface active substances like root and earthworm exudates, transported ash and farm chemicals, soil salinity and generally due to adsorbed impurities that affect adsorption and desorption of water to soil particles (Hillel, 1998; Shukla and Lal, 2004). Hence, contact angle is less for receding than advancing meniscus.

The entrapped air in a blind or dead end is also the cause for the soil water retention curve hysteresis. Encapsulated air may be subsequently liquefied but retards the process of wetting and reduces soil wetness (Hillel, 1998). The phenomenon of soil moisture hysteresis is more noticeable in clay soils with mainly 2:1 clay minerals (Shukla and Lal, 2004). This type of soil has swell-shrink behaviour depending on drying/wetting condition. Alternative thawing/freezing in addition to the previous condition alters soil structure and pore size distribution.

3.3.2 Most Commonly used Hysteresis Branch of Soil Water Retention Curve

Due to hysteresis, SWRC becomes very complicated. To avoid this complication, the desorption method is used (Hillel, 1998). According to Kutilek and Nielsen (1994) the procedure for determining the main wetting or sorption branch of SWRC is difficult as wetting an initially dry sample for a different equilibrium value of suction needs an extremely long amount of time. On the other hand, according to Fredlund (2002) measuring the other branch of the main SWRC is easier and rapid. In this method the fully saturated sample is subjected to a suction value starting from zero and extends to high suction at which water content becomes minimal.

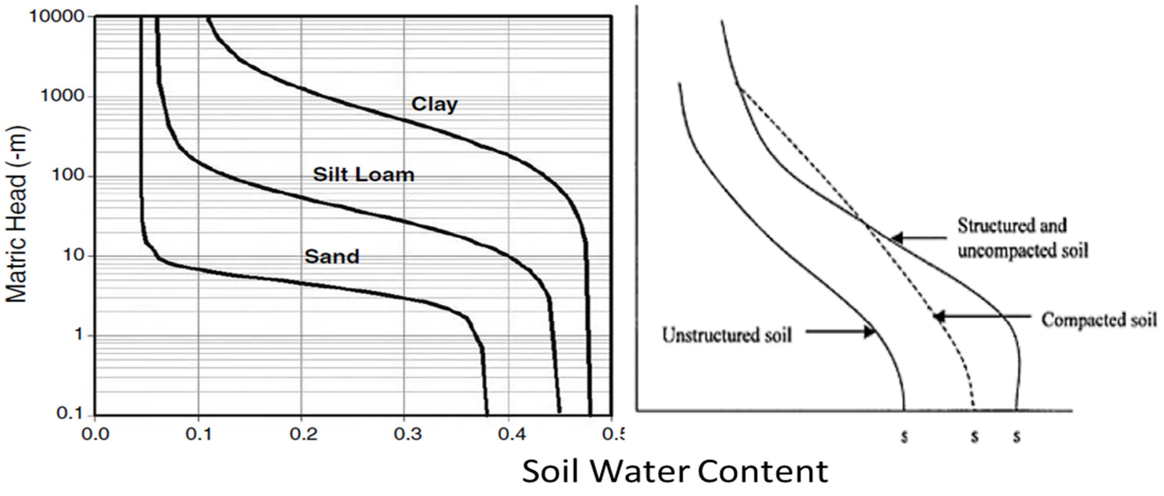
3.4 Factors that Affect Soil Water Retention Curve

We do have different soil water retention curves for a given soil due to soil water retention curve hysteresis. We have seen that we can avoid this difficulty by using one main branch of soil water retention curve hysteresis and get one SWRC for a given soil. However, many other factors affect soil water content-energy relationship (Soil water retention curve). According to Wraith and Or (2002) and Ali (2010) soil texture, soil structure, and soil organic matter content affects SWRC. According to Mukherjee and Biswas (1994) texture and structure are the two most important factors. Additionally, other factors like soil water chemistry (Dawson et al. 2008) and temperature (Kutilek and Nielsen, 1994) can affect soil water retention curve.

3.4.1 Texture

One soil type differs from another by its texture i.e. particle size distribution. The shape and range of SWRC is strongly affected by texture of the soil as pore distribution and size of pores are affected by soil textural distribution (Hillel, 1998). He further explained that for a given suction, more water is retained in clayey soil (soil with greater clay content) than in loam or sandy soil (soil with greater sand content). Likewise, according to Brady and Weil (2004) the water is held much more tenaciously in the former one than the other two at given moisture content. Moreover, less water is retained in the latter soil types as it has relatively lager pores and they release their water at lower suction; while clayey soils release their water slowly with increasing matric suction as they have smaller and uniformly distributed pores which is good for water adsorption. Furthermore, according to Brady and Weil (2004) the clay particle is negatively charged and the water molecule exhibits polarity; so the positive (hydrogen) end is attracted to clay surfaces (adhesion) and the negative (oxygen) end to other water molecules (cohesion). This enables clay soils to hold more water and other cations. According to Mukherjee and

Biswas (1994) the rate of water release in response to applied suction is slow in fine-textured soils but relatively sharp in coarse-textured soils. Generally, according to Miller et al. (2002) soils with larger particle sizes (sand and silt) have smaller air-entry suction and smaller saturated and residual water content compared with that of clay.



(a) (b)

Fig. 3.4. (a) soil water retention curves for three soil textures (from Wraith and Or, p.73.) (b) Effect of soil structure on pF curve (Shukla and Lal, p.321)

3.4.2 Structure

In addition to texture, the SWRC is strongly affected by soil structure which is an important property due to pore size distribution and interconnectedness (Lieth and Ravij, 2008). Well-structured soil has more pore spaces compared to poorly-structured or compacted soil and hence according to Brady and Weil (2004) the former with more pore spaces has greater water holding capacity. According to Shukla and Lal (2004) a strong inflection point of the curve is the characteristic of a soil with good structure while weakly structured or structure less soils do not have well defined inflection points. Disturbances of the structure during agronomic, engineering or other activities which can alter the bulk density of the soil can result in changing the soil water retention curve (Miyazaki, 2006). According to Shukla and Lal (2004) soil structure change over time can be evidenced from the plot of SWRC slope versus pressure head i.e. $d\psi_m/d\theta$ vs ψ_m. Compaction increases soil bulk density by reducing the total porosity (reduce the volume of large pores, increase the volume of intermediate-size pores while the volume of micro pores is unaffected), this results in the reduction of saturated water content and an initial decrease of the water content (Hillel, 1998).

At lower suction non-compacted soils release more water compared to compacted soils and SWRC is more characterized by structure than its texture; however, at higher suction, as the volume of micro-pores is not affected by compaction and the suction is more adsorptive than capillary, the SWRC of both compacted and non-compacted tend to converge and hence it is more affected by texture than structure (Walczak et al., 2004). Hence, according to Brady and Weil (2004) less water retained mostly in small and midsize pores characterize compacted soil. According to Wraith and Or (2002) SWRC at lower suction is more strongly affected by structure than texture and hence it is preferable to analyse undisturbed samples over repacked samples for its wet end.

3.4.3 Organic matter content

Organic matter content influences SWRC directly or indirectly. Generally, increasing soil organic matter content increases soil water retention capacity in both adsorbed and absorbed form (Shukla and Lal, 2004). Depending on the morphological structure of organic matter according to Stevenson (1994) and cited by Bross and Baldock (2012), soil organic matter can absorb and hold up to 20 times its mass. According to Anderson and Schaetzl (2005) this property of the organic rich soil is due to the affinity of water molecules to form H-bonds with NH and OH groups from organic matter. Surface organic matter residue according to Bross and Baldock (2012) increases soil water retention by reducing evaporation. Indirectly, organic matter plays a key role in soil aggregation and pore size distribution. According to Bross and Baldock (2012) it is due to this indirect effect for which soil organic carbon content is included as a significant parameters in pedotransfer function for SWRC estimation. According to Shukla and Lal (2004) organic matter content affects SWRC similar to structure at lower suctions while SWRCs for different organic matter contents tend to converge at higher suction. This convergence shows that soils with high organic matter content have high available water for plants (Mukherjee and Biswas, 1994). They further added that organic matter content of a given soil has little role on permanent wilting point as it is more influenced by mineral soil, particularly clay content.

3.4.4 Soil water chemistry

SWRC is also affected by pore water chemistry (Dawson et al. 2008). When there is a solute in soil water, SWRC which is the function of soil water content versus matric potential is not sufficiently defined as osmotic potential affects the flow of water by reducing total potential energy of water which in turn reduces water movement (Miyazaki, 2006). This reduction according to Brady and Weil (2004) is due to clustering of water molecules around solute ion or molecule. Miyazaki (2006) explained that the amount of osmotic potential contributed is related to sizes of pores, electrical properties of solid surfaces, type and concentrations of ions in soil solution. According to Brady and Weil (2004) osmotic potential is lowered by increasing the concentration and hence water tends to move to the zone of higher solute concentration. It affects water and solute movement and their direction when the pores restrict the passage of salts (solute) but not of the water molecule from forced solution through soil (Shukla and Lal, 2004). However, according to Brady and Weil (2004) liquid water moves by leaving the solute behind through a semi permeable membrane which doesn’t exist in natural soil but on plant root cells. However, according to Miyazaki (2006) hydrated solute molecules are less than the pore sizes of sandy soils but occasionally greater than that of clayey ones and hence more water is retained in clayey soils at a given suction due to osmotic potential.

3.4.5 Temperature

Temperature is the average heat or thermal energy of the system and its gradient according to Miller and Nelson (1992) influence the migration of water. It influences the movement by affecting the viscosity of the water according to Shukla and Lal (2004). They are inversely related and increased temperature eases water movement. Hence, soil loses water as evaporation or downward movement under higher temperature and soil retains more water under lower temperature than under higher temperature. Surface tension, viscosity and other properties of the water are highly dependent on temperature and hence temperature has an effect on soil water retention curve, all other factors remain the same (Kutilek and Nielsen, 1994; Shukla and Lal, 2004).

3.4.6 Representative Elementary Volume

Many soil water properties including soil water retention curve can be affected by sample volume size which is composed of pore (occupied by air and water) and solid particles (in/organic) that forms bulk volume of a soil. Moreover, components that make the bulk volume of the soil vary in their nature from the pore with air through that of with water to inorganic part of the solid soil. If the volume of undisturbed soil sample taken is too small according to Hillel (1998) there is the probability, therefore to be from either the pore or the soil particle components that couldn't represent the property of the given soil and according to Haverkamp et al. (1999) if such too small sample is centered to the pore, the porosity is 100% but if it is from solid soil it will be zero. Moreover, according to Hillel (1998) the value of porosity can vary from zero to 100% depending on the exact location from which sample is taken. However, according to Gorokhovski (2012) the variation can be decreased by increasing the volume size of the sample and possible to get the representative volumes. The minimum volume at which the consistent value gained is known as representative elementary volume (Haverkamp et al., 1999). However, due to the fact that the sample can include some macroscopically heterogeneous components, according to Gorokhovski (2012) increasing the volume of the sample further beyond the mean value can also result in start changing again, see Fig (3.5). Moreover, to analys too big sample is costly, labour and time consuming.

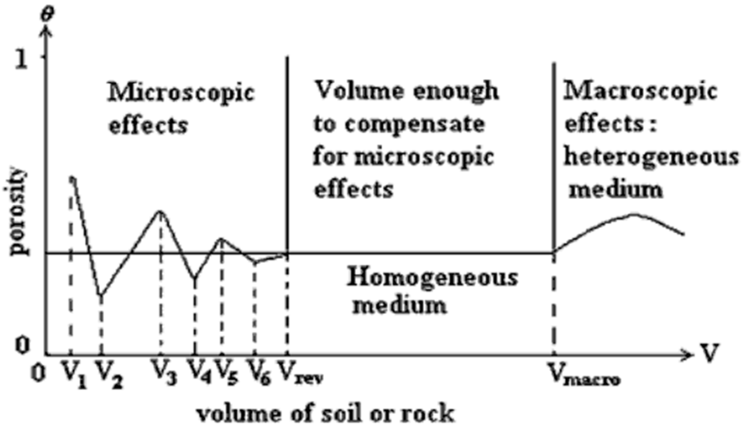


Fig.3.5. Pictorial description of representative elementary volume for porosity (from: Gorokhovski, 2012, p. 23)

3.5 Use of Soil Water Retention Curve

Soil water retention along with hydraulic conductivity controls the hydrology of field soils and they are the two basic properties of soil (Ali, 2010). According to Chan and Govindaraju (2004) and Schaap et al. (2004) they have a strong influence on the movement of water and solute from surface to ground water in the vadose zone. Had there been no water movement in this zone, according to Mukherjee and Biswas (2006) there would probably be no plant growth on the earth’s surface; but it occurs much more often faster than it does in the saturated zone. They further explained that plants continuously take up water through their roots and the immediate vicinity becomes dry and creates naturally high suction. According to them it is this suction which creates potential difference and forces water retained in the surrounding soil to move towards the roots until permanent wilting point (PWP) is reached. Even though all soil water up to this point isn’t readily available to plants, according to Goss and Ehlers (2003) this point is at a matric potential, ψ_m of 15,000 cm or pF 4.2. They added that on the other hand, soil water near to saturation is drained by gravity and hence not used by plants effectively. Plants effectively use soil water from field capacity (FC). However, according to White (2006) this point is not fixed; rather it varies between 60 to 300 cm pressure head corresponding to 1.8 to 2.5 pF. Therefore Soil water content (θ) should be kept between FC and the lower limits of readily available water so that water availability to the plant is not limited.

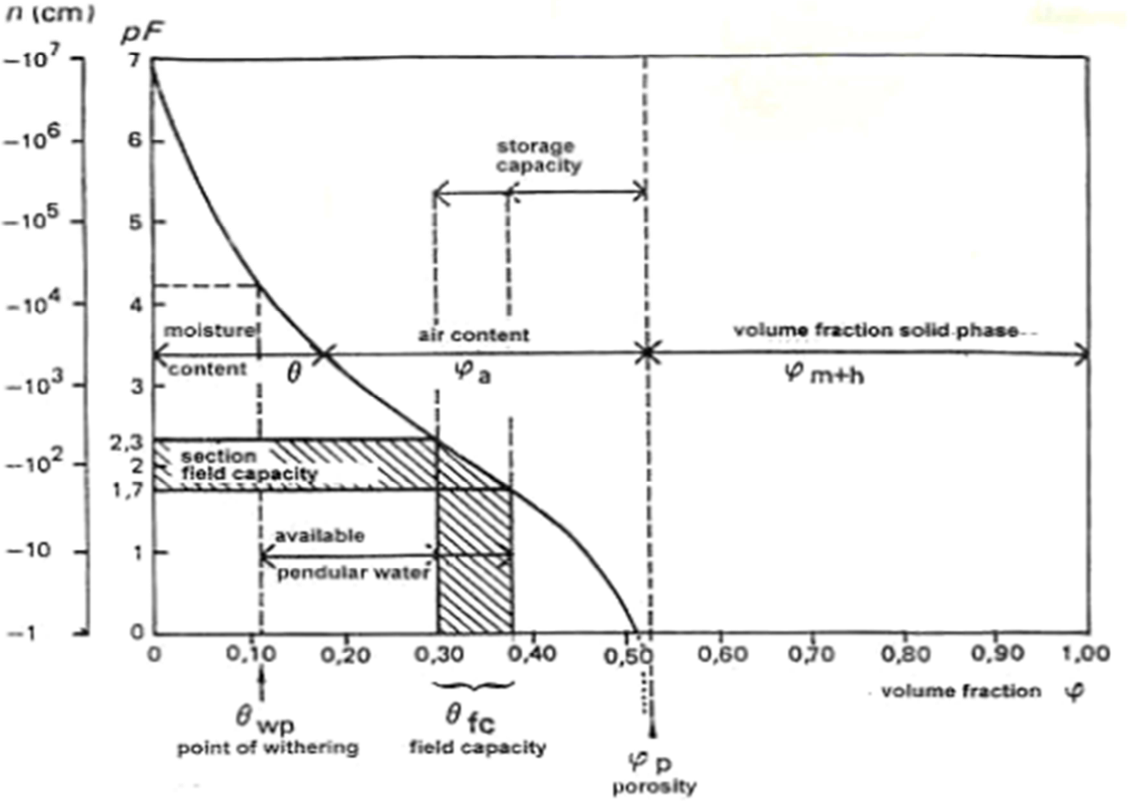


Fig. 3.6. Applications of soil water retention curve (from: Eijkelkamp, online)

Measuring and managing soil water over time according to Morgan et al. (2001) is used to have good crop yield with quality by avoiding both under-irrigation and over-irrigation while saving water, energy and avoiding potential leaching of nutrients and agrochemicals to ground water due to over-irrigation. SWRC is therefore used for predicting or managing water from irrigation or rainfall in porous media (soil) and many more applications related to soil (Wraith and Or, 2002). SWRC is used to predict the maximum specific yield or specific water capacity of a given soil after draining it (Behari, 2005). Specific water capacity according to Shukla and Lal (2004) is defined as the change in water content per unit change in suction and seen as equation (3).

$$C_\theta = d\theta/d\psi_m \ldots\ldots\ldots\ldots(3)$$

where: C_θ is specific water capacity, $d\theta$ is change in volumetric water content and $d\psi_m$ is change in matric suction (unit change in suction)

Hence, SWRC is used in hydrology, agronomical and other agricultural and environmental sciences.

Soil water retention curve according to Fredlund et al. (2001) and Fredlund (2002) also provides useful information to solve geotechnical and geo-environmental engineering problems. It is used to predict unsaturated soil parameters like hydraulic conductivity and permeability (Fredlund and Xing, 1994), shear strength (Fredlund and Rahardgo, 1993) and volume strain and pore size distribution (Zhou and Yu, 2005). Hence, SWRC is useful both in soil physics and soil mechanics.

3.6 Soil Water

According to Shukla and Lal (2004) soil is a warehouse for water and it holds 50 times more fresh water than in rivers and streams. Water occupies soil pore spaces competitively or concurrently with the soil gas phase and according to Wraith and Or (2002) it is dynamic both in time and space. Soil water does not occupy only pore spaces according to Brady and Weil (2004) but also is associated with solid particles and hence it is different from free water in a drinking glass. The water molecule is held to the soil particle by adhesive force while cohesive force maintain more water molecules together which enables the particle to retain a thicker water film. This changes the behaviour of both water and soil particles. Adhesive force restricts free movement of water while water according to Brady and Weil (2004) causes many chemical reactions, shrink-swell of clay soil and form structural aggregates of soil. However, water can move down due to gravity or up due to capillary rise, evaporation and/or plant uptake. The energy status of soil water determines the movement and availability of water to plant and according to White (2006) it is equally important to study soil water energy with soil water content. Soil water retention curve is about these two general kinds of soil water measurements in a functional form.

3.6.1 Soil Water Content

Soil water content can be expressed in different ways like gravimetric water content (ω), volumetric water content (θ) or degree of saturation (S) (Fredlund, 2002).

Further he noted that gravimetric water content expression for soil water is the preference of soil mechanics like geo-technical and geo-environmental engineering; while volumetric water content is for agricultural related sciences: soil physics, soil science, agronomy, etc.

Volumetric moisture content, θ, is the ratio of volume of water in a given soil to bulk volume of the soil (Hillel, 1998). It can be expressed in percentage when multiplied by 100%. Volumetric water content also shows the depth ratio of soil water to that of soil depth or the depth of water per unit depth of soil (Wraith and Or, 2002).

$$\theta = V_w/V_t = V_w/(V_s+V_p) \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where: θ is volumetric water content ($cm^3.cm^{-3}$), V_w is volume of soil water (cm^3), V_t is bulk volume of soil (cm^3), V_s is Volume of the solid soil (cm^3) and V_p is pore space (cm^3)

$$V_p = V_w + V_g \ldots\ldots\ldots\ldots\ldots(5)$$

where: V_g is volume of pore space (cm^3) that is occupied by air or not occupied by water.

If the other variables of the soil water are known, volumetric water can be calculated from them. According to Fredlund and Rahardjo (1993), volumetric water content, θ can be calculated from porosity, degree of saturation, and void ratio:

$$\theta = S*P = S*e/(1+e) \ldots\ldots\ldots\ldots\ldots(6)$$

where: e is void ratio (-), S is degree of saturation (%) and P is porosity (%)

The conversion between gravimetric and volumetric water content requires the knowledge of dry bulk density, ρ_b which can be calculated from the ratio of mass of oven dry soil (at 105^0c for some hours, 24-48 for inorganic soil) to the initial soil volume and density of water, ρ_w (Wraith and Or, 2002). The conversion is as follows:

$$\theta = \omega*\rho_d/\rho_w \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where: ρ_d is dry density of the soil (g/cm^3), ρ_w is density of water (g/cm^3) and ω is gravimetric water content

Gravimetric water content is expressed as mass of water divided by mass of oven dry soil and it is as follows:

$$\omega = M_w/M_s \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

where ω is gravimetric water content (g/g), M_w weight/mass of water (g) and W_s weight/mass of oven dry soil (g)

Soil water content value of a given soil ranges from zero when dry to equal the total porosity when fully saturated. However, according to Hillel (1998) the lower limit of zero is hardly achievable as the total removal of water from a clay particle is difficult and also according to Kutilek and Nielsen (1994) getting the upper limit of total saturation for sandy soil in short time is also difficult due to air bubbles.

Hillel (1998) stated that agronomic, ecological, hydrological and similar other sectors need soil water content measurement for soil's chemical, mechanical and physical relationships. Despite its numerous uses in soil physics and mechanics, due to several difficulties, accurate measurement of soil water content in field conditions has been a challenge (Shukla and Lal, 2004). Some of the difficulties include variability of the soil for water retention even over a short distance due to texture, organic matter content and infiltration rate, difference in evapotranspiration due to cover type and other microorganism activities. Even though there is no standard and universal means of soil water quantification, there are several methods which are broadly divided in to direct and indirect methods (Hillel, 1998).

Directly, it is measured by drying and weighing a known volume of a soil sample. Due to spatial variation and difficulty to get the accurate value on field or in-situ, soil water content is commonly measured in the laboratory from replicate samples collected from the field (Koorevaar et al., 1999). They further explained that the water content of a given soil is conventionally determined after removing water by drying the sample at 105°C. By this method we can measure the volumetric/gravimetric water content of the wet weight, the oven-dried weight and total volume of our sample. The method is called gravimetric method.

$$V_w = (W_w - M_s) / \rho_w \ldots\ldots\ldots\ldots\ldots(9)$$

where V_w is volume of water (cm^3), W_w is wet weight of soil (g), M_s is mass of oven dry soil (g) and ρ_w is density of water (g/cm^3). Hence, we can calculate the θ from equation (3).

This method is direct and relatively inexpensive but it is time and labour-intensive and destructive (Wraith and Or, 2002). According to Hillel (1998) the standard method for oven-drying itself is arbitrary and some clay type soils may contain a significant amount of water at oven-dry temperature, and oxidization and decomposition of organic matter causes mass loss of solid soil.

According to Hillel (1998) direct method is destructive and it does not have a room for repetitive measurement on the same soil. Hence, non-destructive method that requires less time and labour is preferred. There are many such methods to avoid the problems of the direct method. However, according to Hignett and Evett (2008) none of them can measure an accurate value of θ; rather they each measure something else that changes with water content from which the probable value of θ can be estimated after calibration. These methods are indirect methods of soil water determination. Soils which differ in texture and/or structure according to Mukherjee and Biswas (1994) have different water holding capacities and the indirect method is based on the correlation of certain physical and physicochemical properties of the soil with its water content. For some indirect methods that are taken from IAEA paper see the Appendix F.

Every water content measuring method has its disadvantage. Some are expensive, for example: neutron moisture method and TDR, some of them have health risk problems associated with their use, for example neutron moisture method and gamma method; some are effective to a limited depth only like remote sensing which is valid for surface soil (Shukla and Lal, 2004).

3.6.2 Soil Water Energy status (Soil water potential)

Water flow in soil is due to energy gradient i.e. from higher energy to lower energy until the equilibrium with the surroundings is achieved (Brady and Weil, 2004). According to classical physics, kinetic and potential are two main types of soil water energy. However, the flow of water in the soil is quite low and hence kinetic energy which is directly proportional to velocity square is omitted as it is negligible, usually $0.1 mh^{-1}$ (Hillel, 1998; Wraith and Or, 2002). Therefore, soil water is a function of potential energy. Soil water potential according to Shukla and Lal, (2004) is the relative amount of potential energy which exists in the soil water compared to pure water. According to these authors, total water potential is the sum of many different potential and see equation (10).

$$\psi_t = \psi_p + \psi_m + \psi_z + \psi_o + \psi_{en} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

where: ψ_t, ψ_p, ψ_m, ψ_z, ψ_o, and ψ_{en} refer to total, pressure, matric, height or position, osmotic, and envelope/overburden head (cm), respectively.

For saturated soil water content, θ_s does not change and soil water parameters remain constant, the flow of water is due to gravitational, pressure and osmotic components of the total potential. Work done by this energy is positive. The reason for the absence of the two components: envelope and matric are, envelope potential exists when heavy load is applied on the soil and hence neglected for soil that is free from such influence and even under the existence of an external burden it is neglected for sandy soil but the impact is more for soils with higher clay content (Nielsen et al., 1997); while for matric potential, the potential results from the combined effects of capillarity and adsorptive forces within the soil matrix. Hence, it is the characteristics of unsaturated soil and exists exclusively with pressure potential which is the behaviour of saturated soil (Wraith and Or, 2002). The contribution of the Osmotic potential depends on the salt content of the soil solution and type of the soil. Osmotic potential affects the total potential when the salt sieving phenomenon exists, it is the phenomenon that happens when the pores restrict the passage of salts (solute) but not of the water molecule from forced solution through soil and this is neglected in most soils (Shukla and Lal, 2004). Moreover, according to Brady and Weil (2004) liquid water moves by leaving the solute behind if there is a semipermeable membrane which does not exist in natural soil but in the plant root cell and it has little impact on mass movement in soil. However, in clayey soil in a dry condition, osmotic potential has a greater or lesser influence on the flow but as water content increases and the soil becomes moist, it is assumed that the contribution is negligible and the influence is only from the other components (Miyazaki, 2006). Therefore, saturated water flow is due to pressure and gravitational potential.

As we have seen in definition, SWRC is the curve from water content of the soil at respective potential when equilibrium is reached and hence the behaviour of Vadose/unsaturated soil especially after air entry value. Flow of water in unsaturated soil is governed by energy gradient like saturated soil but the components are different. This gradient according to Brady and Weil (2004) is known as matric potential gradient and the water from high matric potential due to a thick moisture film of soil particles to lower matric potential due to thin films. Hence, Water flow due to inherent soil water properties itself and its interactions with its surroundings (Wraith and Or, 2002). The previously mentioned authors stated that pressure potential and matric potential are mutually exclusive as the value for the former is zero for unsaturated and zero for the latter when saturated. From previous discussion, osmotic pressure is zero for moist soils and hence the flow of water in the saturated condition is governed by other potential. However, in unsaturated soils, soil becomes drier and drier as suction increases and according to Golder Associates (2006) SWRC is from matric potential up to 1,500 kPa but from total (matric and osmotic) for above this value. Hence, according to Fredlund and Xing (1994) suction can be either matric or total (matric and Osmotic) potential.

Water in the vadose zone which is analogous to the soil sample for SWRC determination is retained by the interaction of soil particles-water-gaseous interactions. This capillary or adhesion of water to soil particles interaction decreases soil water potential (Miyazaki, 2006). Work done by this energy is negative in contrast to pure water because adsorption forces like adhesion of water molecules to soil particle and solute ion or molecule and cohesion of water molecules reduce freedom of water movement (Brady and Weil, 2004) and matric potential is usually negative (Shukla and Lal, 2004). For the sake of convenience, the way of measuring and computation, potential is usually expressed as potential head (cm or m) see equation (11).

$$\psi = \Phi/\rho_w * g \ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where: ψ is potential head (m), Φ is potential (J/kg), ρ_w is density of water (kg/m^3) and g is acceleration due to gravitaty (m/s^2)

The underlying principle of water retention in soil against applied suction/pressure according to Mukherjee and Biswas (2006) is due to matric or total potential of the soil which is equal in magnitude but opposite in direction with the applied pressure.

Soil water potential either matric or total (matric + osmotic) can be measured using different techniques with different suction ranges. However, the most widely used for low suction is tensiometer (Shukla and Lal, 1998). Even though it is relatively simple, inexpensive and can be easily installed, this method has its limitations as the tensiometer is unsuitable for measuring matric potential of saline soils, restricted to the lower range of suction; it is inserted to limited depth; has a long response time and poor soil contact in gravelly soil.

3.7 Methods of measuring soil water content and energy for soil-water retention curve

Properties of the soil either to store water or to enable its movement are the basic properties of soil. Water is stored or removed from the soil depending on bio-physico-chemical properties of the soil and total potential of soil water. Soil water retention is due to soil texture, structure and organic matter content of the soil, which influence the size and distribution of pores in a given soil (Mukherjee and Biswas, 1994). It is, therefore, very important to know the amount of water retained in a given soil after a portion of water is removed due to the energy gradient.

Soil water retention curve can be measured directly or estimated indirectly. In the direct method, the water content of the soil is directly measured at a different matric potential while in the indirect method the parameters are estimated from different soil characteristics such as particle size distribution, soil structure and organic matter content.

3.7.1 Indirect methods

Direct measurement of data for soil water retention curve in research and application is impractical in the case of a relatively large scale problem (Rajkai et al., 2004). The indirect method of estimation, therefore can be used in some cases as an alternative to the direct method of measurement because soil hydraulic properties like SWRC have large spatial and temporal variability and hence direct measurements are time consuming and expensive (Matula et al., 2007; Ali, 2010; Dashtaki, 2010). Different indirect approaches have been used to estimate an approximate soil water retention curve from the data which can be easily measurable and is more readily available (Barber et al., 2001; Rajkai et al., 2004). This method of SWRC estimation is known as Pedotransfer function (PTF) (Fooladmand, 2011). However, no universal theory exists according to Hillel (1998) for this method of soil water retention curve estimation from basic soil properties. Although Indirect methods for SWRC estimation are cheap and measured from easily available data of regularly measured soil basic properties according to Mohammadi and Vanclooster (2011), its applicability to independent data sets is limited. It relies on empirical coefficients and further according to Wösten et al. (1999) the applicability of PTFs is often limited to the data set used to define the method. Moreover, this approach ignores the necessity of physics that govern the drainage and wetting of soil (Chan and Govindaraju, 2004).

Although bulk density, organic matter content and structural indexes of the soil are used, soil texture is the most common input in PTF (Dashtaki, 2010). The reason for motivation to estimate SWRC from texture/particle size distribution is the similarity between the shape of SWRC and cumulative PSD in addition to easy availability of texture data (Nimmo et al., 2007; Ali, 2010). However, according to Vereecken et al. (2010), the most accurate estimation for SWRC is obtained when textural properties, bulk density, soil organic matter, and soil moisture content are used. After comparing SWRC from PTF with SWRC from experimental data, Barber et al. (2001) suggested that the estimation of SWRC from particle size distribution for silt and sand is promising while that of clay needs more research.

3.7.2 Direct methods

The indirect method, as we have seen in the earlier section, can be used for larger areas with varied soil types as it is difficult to cover the whole area using direct method. Moreover, according to Kastanek and Nielsen (2001), the theoretical relationship between matric potential and soil water content has not been established and hence SWRC models including PTFs are empirical. Therefore it is very difficult to get accurate SWRC as PTF ignores the necessity of soil physics that govern the drainage and wetting of the soil (Chan and Govindaraju, 2004). Moreover, according to Fredlund and Xing (1994) and Fredlund et al. (2001) SWRC has to be reasonably accurate for better use; such as to predict unsaturated soil property functions like permeability, unsaturated hydraulic conductivity and others as it is relatively measured easily. Hence, it is very important to use the direct method to get experimental data for SWRC determination for a given soil.

Direct method is performed through taking a series of measurements of water content at different matric potential (ψ- θ) pairs, when respective equilibrium reached over the wetness range of interest (Wraith and Or, 2002). Experimental data for SWRC can be measured directly in the field or in the laboratory (Kutilek and Nielsen, 1994). Therefore the direct method can be further divided in to two; namely in-situ/field method and laboratory method.

3.7.2.1 Field/in-situ Methods

According to Ramos et al. (2006) due to the larger volume of soil with continuity in the soil profile vs. depth, the field method is usually taken as more realistic than the laboratory method of SWRC determination. It enables observing the soil water property at several depths under natural field conditions (Kutilek and Nielsen 1994). For the estimation of SWRC in the field, matric potential is measured by a tensiometer while neutron moderation, gamma-ray attenuation, TDR, or gravimetric methods are used to determine the volumetric water content and hence according to Vaz et al. (2002) a combination of several methods can be used. However, according to Wraith and Or (2002), suitable measurement techniques are severely lacking even though neutron moisture meter access tube or TDR waveguides for soil water content and tensiometer for matric potential are commonly used to determine SWRC. Kutilek and Nielsen (1994) list the following main disadvantages of the field methods as: labour intensiveness, it is conducted under non-isothermal conditions, it is used to determine only part of SWRC usually up to 750 cm and the main hysteresis branches cannot be determined.

3.7.2.2 Laboratory Methods

The twin variables, water content and matric head, for the determination of the curve have to be measured directly because according to Hillel (1998) translation on the basis of calibration curves is too often unreliable. This is relatively easy in the laboratory (Fredlund et al., 2001) and according to Fredlund et al. (1996) SWRC is determined accurately through lab experimentation. In the laboratory, soil moisture content and matric head are often measured using tension plate assembly in the low suction (< 1 bar) range and by means of a pressure plate or pressure membrane apparatus in the higher suction range (Hillel, 1998; Walczak et al., 2004). A significant amount of water is released from soil within a low tension range compared to that of the higher suction range and hence it is very necessary to measure the soil moisture retained at lower suction against applied pressure (Ali, 2010). He further explained that due to the inherent structure of the pressure plate and difficulty in fixing up tension at lower tension for the purpose, different techniques such as: porous plate, sand table or hanging column method is used. However, both pressure plate and those apparatus used to measure at lower suction allow the application of a successive pressure value and measurements of soil moisture at equilibrium for the respective value (Walczak et al., 2004).

Initially, the soil sample has to be saturated prior to the application of pressure. The sample is placed on a layer of fine sand saturated with water in a sand tank that is connected hydraulically to an outflow vessel according to Kutilek and Nielsen (1994). They added that water in the vessel should be kept in the same position with that of the sample in the sand tank for the saturation to the extent practically possible. Alternatively, samples can be saturated on a saturation mat. However, the saturated samples on the saturation mat also have to be kept in the sand tank with the same level with water in the vessel before starting pressure application to ensure enough hydraulic contact between the sample and sand in the sand tank. Then after, under pressure or tension is created and maintained to the system by lowering the water level (Kutilek and Nielsen, 1994). According to Ali (2010) tension is transmitted to the samples through porous media on which they are kept, which allows the water outflow from the samples until the equilibrium between applied suction and matric potential from the soil- water is reached. The soil water content of the sample(s) at equilibrium is measured either gravimetrically or from the volume of the outflow in the case of a single sample. This procedure continues until the air entry value of the sand in sand tank is reached which is most of the time less or equal to 100 cm if the soil air is kept under atmospheric pressure (Hillel, 1998).

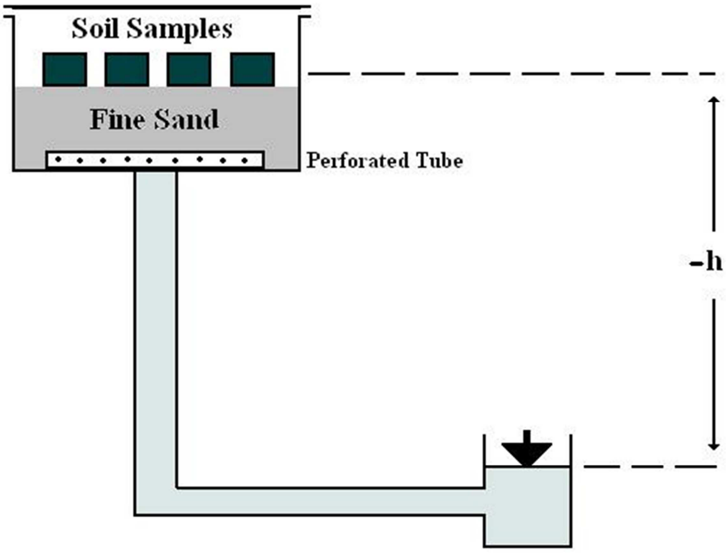


Fig. 3.7. Diagram of Sand tank with drainage pipe at the bottom (from Kutilek and Nielsen, p. 74)

SWRC in the higher suction range according to Walczak et al. (2004) is measured by means of a pressure plate or pressure membrane apparatus. Pressure plate apparatus can be used for the pressure head less than 1500 cm (200-1500 cm) according to Fredlund et al. (2001). However, according to Cresswell et al. (2006) at 1500 cm, suction might not be at real equilibrium. The apparatus consists of a pressure chamber enclosing a water saturated porous plate on which sample(s) are kept that allows water flow but not air through its pores within the range of applied pressure (Wraith and Or, 2002). They further explained that the upper surface of the plate is at the applied pressure of the chamber while the bottom is open to atmospheric pressure. Thus according to Cresswell et al. (2006) this creates a hydraulic gradient and subsequent flow of water from the samples through the saturated ceramic plate until the soil samples reach equilibrium with the imposed pressure which in theory, outflow ceases. In contrast to creating under pressure or tension by lowering water level in sand tank according to Kutilek and Nielsen (1994) pressure in the pressure plate is over pressure which is created by increasing the air pressure over the porous plate that is hydraulically connected to the outflow vessel, usually a burette. Soil water content is measured in a similar way to that from a sand tank, after equilibrium is reached for successive pressure application for the range of applied pressure.

The laboratory method has advantages according to Kutilek and Nielsen (1994) in analyzing large number of soil cores at the same time; is not labour-intensive; flexible in application of suction; no variation in temperature as it is performed at room temperature. However, they also stated the following disadvantages of the method; the sample may be too small to represent the real case, there may be too long a time for equilibrium, it may be damaging to larger pores during sampling, except for sandy soil owing to the way of application of suction and soil water content near saturation may not be accurate.

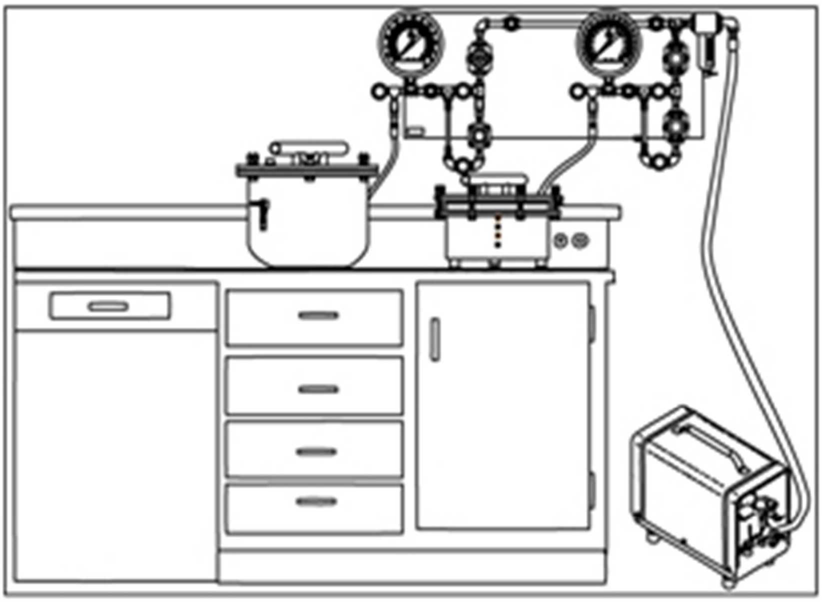


Fig. 3.8. Diagram of Laboratory setting of pressure plate apparatus (Soilmoisture, online)

Even though the focus was given to those methods used only during my laboratory work, there are some other laboratory methods used for SWRC measurement. These include: Tempcell, pressure membrane, vacuum extractor, evaporation method, etc.

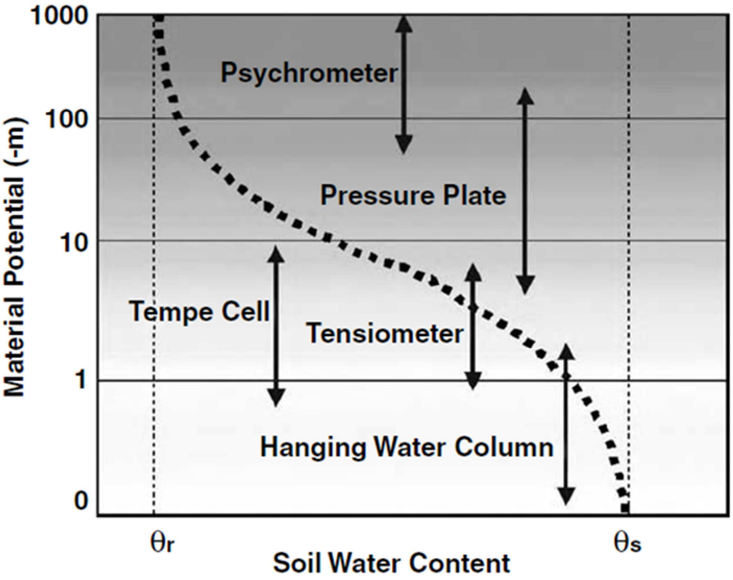


Fig. 3.9 Typical ranges of application for some common matric potential measurement or inference methods (from: Wraith and Or, p.76)

3.8 Fitting Experimental Data

According to Fredlund and Xing (1994) and Fredlund et al. (2001) SWRC is used to predict unsaturated soil property functions and has many other uses and hence it is very important to have a reasonably accurate curve. However, according to Khlosi et al. (2008) data sets that are obtained from either laboratory or field measurements are discrete (θ, ψ); while Soil water retention curve is a continuous function. However, it is impossible to measure every point of the curve and measured fragments (θ-ψ) constitute relatively very few parts of the curve (Wraith and Or, 2002). Additionally, it is time and labour intensive to measure those points by itself. However, having a continuous and parametric form of SWRC is very important according to Wraith and Or (2002) for the characterization and comparison of different soils and scenarios and for modelling and analysis. Hence, a number of mathematical functions have been proposed to show the relationship of water content and matric potential in order to have a better soil water retention curve (Ali, 2010). However, as most of the mathematical functions developed for SWRC are empirical according to van Genuchten (1980) their application to actual field conditions is limited by the lack of information regarding the parameters entering into these equations. Hence, according to Hillel (1998) many of them have been proposed for some soil types and within limited suction ranges. Due to the effect of adsorption and pore geometry it is difficult to describe SWRC by a simple model he added. Wraith and Or (2002) elaborate that the best mathematical equation for soil water retention curve modelling should have few parameters for ease of estimation and describe its stages while fit the measured data closely.

Some of the empirical equations do not model the whole suction range as the curve is asymptotic to the vertical line at both its marginal stages i.e. boundary stage effect (0 to air entry suction) and residual stage (Fredlund et al., 2001). They further explained that the value of water change will be zero if the curve is extended to the negative suction range which is in reality to positive pore water pressure and the value of water content will not be zero if the 10^6 kPa suction is applied. Previous experiments show that soil suction reaches its maximum of 10^6 kPa when water content becomes minimum i.e. zero (Fredlund and Xing, 1994).

Therefore, it is important to use the most widely used method which gives a relatively better soil water retention curve.

Except for the boundary effect part, according to Kutilek and Nielsen (1994) and Hillel (1998), SWRC resembles hyperbola and it is advantageous to use the equation of hyperbola for the solution of practical problems which for hyperbola uses the following equation:

$$\Psi_m = a\theta^{-b} \ldots\ldots\ldots\ldots (12)$$

where: Ψ_m is matric suction, θ is volumetric water content and a and b are empirical constants

The equation is not applicable to the range of the moisture near saturation and fits only to a limited part of the curve and hence according to Hillel (1998) is used for describing change of moisture with in a relatively narrow range.

Several empirical equations have been developed for SWRC modeling. Many of them according to Kastanek and Nielsen (2001) have been developed for soil water content from saturation to permanent wilting point of plants. Fredlund and Xing (1994) stated that none of the developed equation appears to fit the experimental data over the entire suction (0 to 10^6 kPa). The factor which precludes the accurate description of SWRC according to Kastanek and Nielsen (2001) is the absence of a developed theoretical relationship and the equations remain empirical. The most widely used and adopted for SWRC description according to Prunty and Casey (2002) are Brooks and Corey (1964) and Van Genuchten (1980).

Brook and Corey (1964): is denoted as BC (Fredlund and Xing, 1994; Wraith and Or, 2002).

$$\Theta = \left(\frac{\psi_e}{\psi}\right)^{\lambda} \text{………13a}$$

where ψ_e is air entry suction, λ is the pore size distribution index which affects the slope of the curve, which is the characteristic of the soil with values approximately equal to 2 to 5. λ is large for soil with uniform pore size distribution and small for soil with a wide range of pore sizes. Θ is effective/normalized water content and defined as follows:

$$\Theta = \left\lfloor \frac{\theta - \theta r}{\theta s - \theta r} \right\rfloor = \left(\frac{\psi_e}{\psi}\right)^{\lambda} \text{……….(13b)}$$

$$\Theta = 1 \qquad \psi \leq \psi_e \text{………(13c)}$$

$$\Theta = \left(\frac{\psi_e}{\psi}\right)^{\lambda} \quad \psi > \psi_e \text{……….(13d)}$$

Or according to van Genuchten et al. (1991) it can be written as follows:

$$\theta = \begin{cases} \theta_r + (\theta_s - \theta_r)(\alpha\psi)^{-\lambda} \rightarrow for(\alpha\psi > 1) \\ \theta_s \rightarrow for(\alpha\psi \leq 1) \end{cases} \text{……….(13e)}$$

where: all the parameters remain the same except for α which is an empirical parameter $(L)^{-1}$ whose inverse is often mentioned as an air entry suction or bubbling pressure and seen as follows: $\psi_e = \frac{1}{\alpha}$

After rearrangement:

$$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{\psi_e}{\psi}\right)^{\lambda} \text{…………..(13f)}$$

where θ is the volumetric water content which is the function of suction, θ_s is maximum wetness i.e. saturation or near to it, θ_r is the residual wetness remaining even at high suction. The equation is commonly called normalized water content equation. It is used to study the soil behaviour between saturation and residual water content and enables the separation of physical behaviour from saturated to residual conditions (Fredlund, 2002).

Van Genuchten (1980): commonly denoted as VG (Wraith and Or, 2002)

$$\theta_E = \left[\frac{\theta - \theta r}{\theta s - \theta r}\right] = [1 + (\alpha * \psi)^n]^{-m} \text{…………………..(14a)}$$

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha * \psi)^n\right]^m} \text{………………………………..(14b)}$$

where: α, n, m empirical constants that affect the shape of the retention are curve and $\alpha > 0$; $n > 1$; $|\psi| \geq 0$; $0 < m < 1$. The value of n is between 1.2 and 4 while that of α is between 10^{-3} to10^{-2} $cm^{-1.}$

van Genuchten function's or simply VG equation is very useful according to Miyazaki (2006) within the range of θ_s and θ_r but not for the residual stage of SWRC as it is not easy.

Every general empirical equation according to Fredlund and Xing (1994) has its own limitation in fitting the experimental data reasonably well over the entire suction range. They propose the model developed depending like other models on pore size distribution from which SWRC is uniquely estimated. However, unlike other models it is valid for the entire range of suction i.e. from 0 to 10^6 kPa and fits the experimental data over this range (Fredlund et al., 2001). The equation is empirical but derived by assuming that the soil has interconnected and randomly distributed pores.

Fredlund and Xing (1994):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left\{ \ln\left[e + \left(\frac{\psi}{a} \right)^n \right]^m \right\}} \quad \ldots\ldots\ldots\ldots\ldots(15)$$

where: θ is volumetric water content at a given suction ψ; θ_r volumetric water content at residual condition; θ_s volumetric water content near or at saturation; a, n and m are empirical constants that affect the shape of Soil water retention curve; a is a suction value related to the inflection point of SWRC which has physical meaning in its relationship to the air entry value of the soil, n is corresponding to the slope of SWRC in the transition stage and m is related to the residual water content.

4. Material and Methods

The purpose of this study was to evaluate the difference in soil water retention curves (SWRC) of a homogeneous porous material (silica sand) packed into the two most commonly used rings (core samplers): 100cm^3 and 250cm^3. Samples were prepared in the laboratory from silica sand for this purpose. The sand was packed into each ring layer by layer with gentle compaction to obtain a uniformly distributed sample along the sample column. Prepared samples were saturated and suction or pressure was applied to them first in the sand tank and later in the pressure plate for SWRC development and evaluation.

4.1 Silica sand

Soil used for this study was silica sand with commercial name ST 56 from Střeleč area in East Bohemia and produced by Sklopísek Střeleč, a.s., Czech Republic. The work of the company is to prepare different types of silica sands which can be raw materials for different purposes. Střeleč silica sand ST 56 is used for surfaces/top cover of sport pitch. The company provides silica sand in dry/wet state either in bulk or in bags. The sand ST 56 for this experiment was dry and supplied in a bag.

It is called silica sand because its silica (silicon dioxide) content is 98.9%, see Table (4.1). It has an average value of pH 8.0, typical total porosity 37.3% and particle density 2.65 g/cm^3. For more physical properties of this sand see Appendix B.

Table 4.1. Chemical Analysis of Silica Sand (according to Sklopísek Střeleč, a.s.)

N<u>o</u>	**Chemical Compound**	**%**
1	SiO_2	98.9
2	Fe_2O_3	0.07
3	$K_2O + Na_2O$	0.2
4	CaO + MgO	0.2

Particle size distribution for this silica sand ST 56 ranges from 0.063 mm to 0.40 mm with the middle grain size (d50) of 0.15 mm, but it contains few silt/clay particles up to 2.2%. However, the silica sand ST 56 is free from stones, gravel and very coarse sand, see table (4.2). Particle size distribution for this sand is given in Appendix C and particle size distribution curve is given in fig. 4.1.

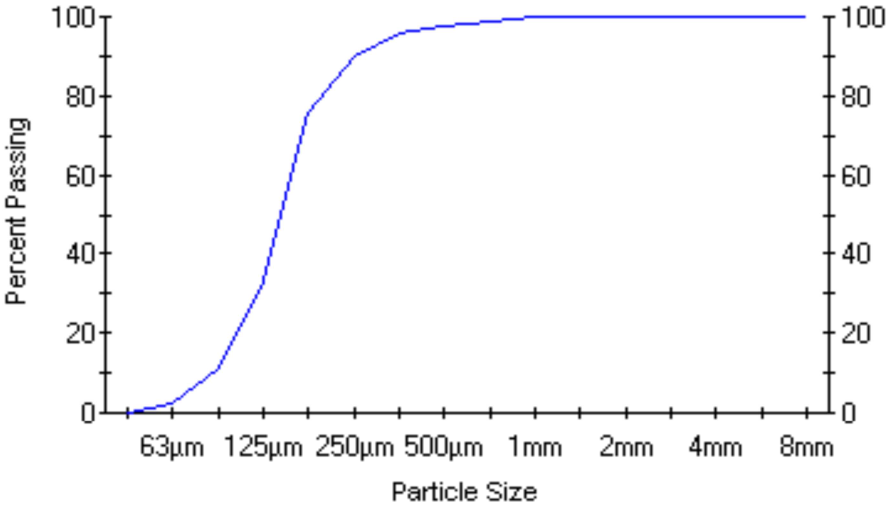


Fig. 4.1. Particle Size Distribution curve for Silica Sand ST 56

Table 4.2. Texture of Silica Sand ST 56 (according to Sklopísek Střeleč, a.s.)

Category	**Diameter (mm)**	**% Retained**
Stones	>8	0
Coarse Gravel	8 to 4	0
Fine Gravel	4 to 2	0
Very Coarse Sand	2 to 1	0
Coarse Sand	1.0 - 0.5	2.1
Medium Sand	0.5 - 0.25	8
Fine Sand	0.25 - 0.125	56.9
Very Fine Sand	0.125 - 0.063	30.8
Silt/Clay	<0.063	2.2

4.2 Soil sample preparation

Soil was packed into two types of soil core samplers with 50 mm in height, one of 100 cm^3 volume with radius 25.23mm and the other one of 250 cm^3 volume with radius 39.89mm. For each type of core sampler, 9 replicates were prepared; 7 for SWRC determination and 2 for moisture content distribution of the prepared samples after saturation.

Samples were packed in each ring to obtain constant dry bulk density. The dry bulk density is a fundamental soil physical property, according to Assouline (2006), which shows the porosity and compactness of a given soil. The bulk density for this sand, according to the secondary data from Sklopísek Střeleč, a.s., is on average 1.5 g.cm^{-3}. The mass of the soil to be packed was calculated from the desired density and the volume of the rings. Not to overcompact the samples, which would affect the void volume of the soil, according to Assouline (2006), 1.48 g.cm^{-3} density was chosen. Hence, the mass of dry soil to be packed into the two types of rings was as follows: in the small ring with the volume 100 cm^3, it was 1.48 g.cm^{-3}*100 cm^3= 148g, while in the bigger ring with the volume of 250 cm^3 it was 1.48 g.cm^{-3}*250 cm^3=370g. The digital balance used for the whole process was Kern 572 with measuring capacity up to 810g and sensistivity d=0.01g. However, as it is very difficult to pack the soil, especially sandy soil, while it is dry, 10% by mass of water was added to the sample. The sample was mixed with water uniformly in a ceramic dish. The mass of moist sample packed into each of the two types of ring was as follows: in the small ring the wet mass was 148g + 0.1*148g = 162.8g, while in the bigger ring it was 370g + 0.1*370g = 407g. However, it is difficult to put the whole sample into the ring at once and get uniformly distributed soil column. Hence, the sample was filled layer by layer by dividing the height of the ring into five equal parts; 50mm/5 = 10mm each. The mass of wet soil in each layer was: for the small ring 162g/5 = 32.56g, while for the bigger ring 407g/5 = 81.4g, assuming that the mass of dry sample in each layer was: in the small ring 148g/5=29.6g, while in the big ring it was 370g/5=74g. The given mass in each layer, starting from the bottom one, was compacted slowly/gently to ensure both uniformity and intended density of the soil in each ring for all prepared samples for the experiment. To prevent the loss of the sand through the smapler bottom, the lower opening of the ring was cover with geotextile and tied to the ring by rubber band.

The prepared samples were kept on the saturation mat for 48 hours to ensure full/maximum saturation by capillarity. After their maximum saturation, 2 samples from each category were taken randomly for the observation of moisture distribution in each layer. A small disturbed sample was the taken from each layer (depth range) i.e. 0-10, 10-20, 20-30, 30-40 and 40-50mm downwards of the two rings. It was oven-dried for 24 hours at 105^0C and its gravimetric water content was calculated. The other seven replicates for each ring type were taken for SWRC analysis.

4.3 Soil water retention curve determination

To get experimental data for soil water retention curve determination, successive suctions/pressures were applied to the samples, starting from saturation. The samples' weights at respective suction/pressure steps were determined at equilibrium. Samples were subject to several suction values in the sand tank and later they were transferred to the pressure plate for a higher pressure.

In the sand tank, the saturated samples were fully covered to avoid water loss due to evaporation and underpressure/tension was applied to them via the sand tank. The sand tank used for the purpose has a drainage pipe at the bottom of the sand layer connected to a vessel for outflow measurement and a Mariotte bottle for tension application and management by lowering it. After the application of the tension by lowering the Mariotte bottle, the outflow condition was recorded. When the outflow finished, the weight of each core sample was taken at equilibrium. In the sand tank, a series of underpressures (tensions): 0, 5, 22, 40, 55 and 70 cm was applied and the respective weights of all samples were taken as soon as equilibrium was reached. Due to the relatively low air entry value of the sand in the tank, the sand tank cannot be used for higher suctions (Kutilek and Nielsen, 1994).

After using the sand tank for lower matric heads over the range of applicability (0 to 80 cm), the samples were transferred to pressure plate for higher pressure application. Pressure plate apparatus used for this purpose was Ceramic Plate Extractor model CAT #1500, Soil Moisture Equipment Corp., with pressure limit of 15 bars. The ceramic plate of the pressure plate apparatus was saturated under submerged conditions. Immediately after the plate was fitted in the pressure apparatus, the samples from the sand tank were transferred to it and placed upright on the saturated plate. After closing the pressure plate apparatus properly, 2.3 bar overpressure was applied and outflow to the burette, which is connected hydraulically to the apparatus, was recorded. Weight of each sample was taken at equilibrium.

Data from both apparatus were used to construct soil the water retention curve. Both measured and fitted data were analyzed. Measured data were fitted to the Brooks-Corey, van Genuchten (with m and n independently optimized, m=1-1/n and m=1-2/n,) and log-normal distribution models/equations, using RETC (RETention Curve) computer program (software).

5. Results

Soil water retention curves for the two sizes of core samples were derived from the data obtained from sand tank and pressure plate. The experimental data were fitted to different models developed for such purpose. Both the measured data and the fitted data obtained from the models that fitted the measured data best were evaluated, as for the effect of the core sample sizes on the soil water retention curve.

5.1 Moisture distribution throughout the sample column at saturation

Table 5.1. Mass of saturated soil, oven-dry soil and water in each layer of the core sample for vertical moisture distribution

Ring	**Mass (g)**	**Depth (mm)**				
		0-10	**10-20**	**20-30**	**30-40**	**40-50**
S8	Tare	61.49	60.42	68.6	61.5	62.9
	Saturated soil + tare	77.96	75.47	84.99	77.08	78.92
	Oven dry soil + tare	74.42	72.24	81.45	73.82	75.58
	Saturated soil	16.47	15.05	16.39	15.58	16.02
	Oven-dry soil	12.93	11.82	12.85	12.32	12.68
	Water	3.54	3.23	3.54	3.26	3.34
S9	Tare	63.74	59.16	66.58	70.63	66.63
	Saturated soil + tare	81.69	76.74	85.17	90.43	87.24
	Oven dry soil + tare	77.83	72.98	81.21	86.22	82.92
	Saturated soil	17.95	17.58	18.59	19.8	20.61
	Oven-dry soil	14.09	13.82	14.63	15.59	16.29
	Water	3.86	3.76	3.96	4.21	4.32
B8	Tare	67.39	72.68	71.31	85.44	90.33
	Saturated soil + tare	97.59	107.04	108.93	122.62	130.06
	Oven dry soil + tare	91.15	99.69	100.91	114.8	121.66
	Saturated soil	30.2	34.36	37.62	37.18	39.73
	Oven-dry soil	23.76	27.01	29.6	29.36	31.33
	Water	6.44	7.35	8.02	7.82	8.4
B9	Tare	60.49	69.39	58.61	63.84	69.7
	Saturated soil + tare	98.15	107.9	96.96	101.63	106.81
	Oven dry soil + tare	89.97	99.6	88.71	93.75	99.13
	Saturated soil	37.66	38.51	38.35	37.79	37.11
	Oven dry soil	29.48	30.21	30.1	29.91	29.43
	Water	8.18	8.3	8.25	7.88	7.68

Gravimetric water content of each 10 mm layer was evaluated for obtaining moisture distribution along the 50 mm sample column for the two sizes of core samples (100 cm^3 and 250 cm^3). The disturbed samples were taken from the top downward. The core samples for the study consisted of rings packed with silica sand and subsequently saturated by capillarity. Their vertical moisture distribution was observed for the purpose of testing the homogeneity of the sample throughout the soil column. Mass of saturated soil, mass of oven-dry soil and mass of water at each layer is presented in table 5.1.

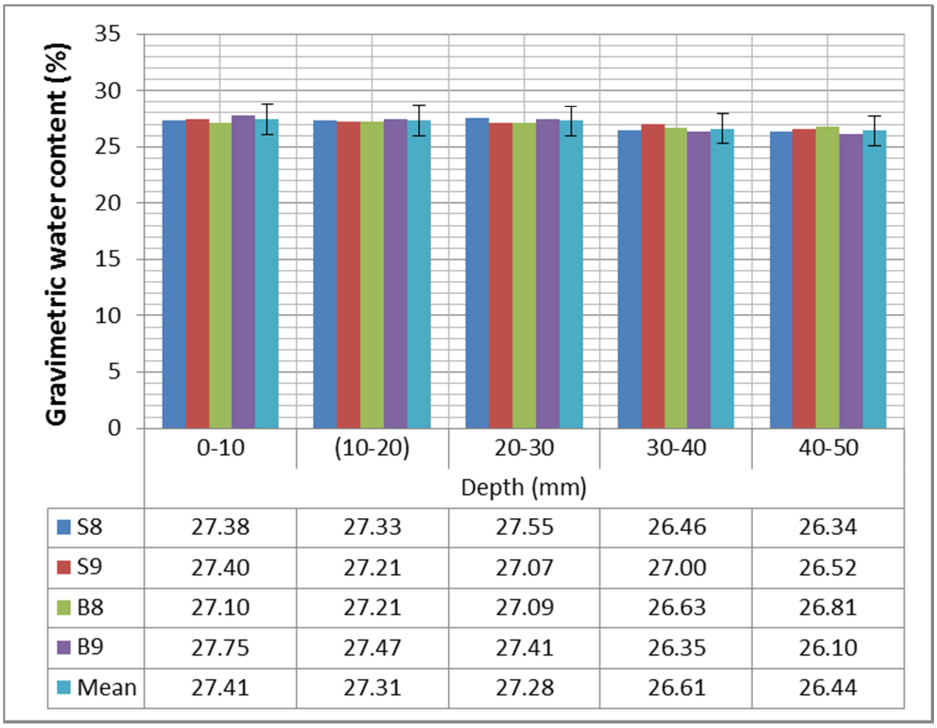
Gravimetric water content ($g.g^{-1}$and %) for every 10mm depth of the ring, starting from its top, was calculated using eq. (5) and is presented in table 5.2.

Table 5.2. Gravimetric water content for every 10mm depth of the core sample ($g.g^{-1}$ and %)

Ring	Mass (g)	Depth (mm)				
		0-10	10-20	20-30	30-40	40-50
S8	Oven dry soil	12.93	11.82	12.85	12.32	12.68
	Water	3.54	3.23	3.54	3.26	3.34
	Gravimetric water content (g/g)	**0.2738**	**0.2733**	**0.2755**	**0.2646**	**0.2634**
	Gravimetric water content (%)	**27.38**	**27.33**	**27.55**	**26.46**	**26.34**
S9	Oven dry soil	14.09	13.82	14.63	15.59	16.29
	Water	3.86	3.76	3.96	4.21	4.32
	Gravimetric water content (g/g)	**0.2740**	**0.2721**	**0.2707**	**0.2700**	**0.2652**
	Gravimetric water content (%)	**27.40**	**27.21**	**27.07**	**27.00**	**26.52**
B8	Oven dry soil	23.76	27.01	29.6	29.36	31.33
	Water	6.44	7.35	8.02	7.82	8.4
	Gravimetric water content (g/g)	**0.2710**	**0.2721**	**0.2709**	**0.2663**	**0.2681**
	Gravimetric water content (%)	**27.10**	**27.21**	**27.09**	**26.63**	**26.81**
B9	Oven dry soil	29.48	30.21	30.1	29.91	29.43
	Water	8.18	8.3	8.25	7.88	7.68
	Gravimetric water content (g/g)	**0.2775**	**0.2747**	**0.2741**	**0.2635**	**0.2610**
	Gravimetric water content (%)	**27.75**	**27.47**	**27.41**	**26.35**	**26.10**

The samples from the saturated soil in the ring were taken from the top downwards. The maximum differences between different layers of the same sample were evaluated. The maximum among these differences was found between the first and the fifth layer of

B9, which was 1.65% by mass, while the least one was between the first and the fourth layer of B8, which was 0.47% by mass, see table. 5.2.



	0-10	(10-20)	20-30	30-40	40-50
S8	27.38	27.33	27.55	26.46	26.34
S9	27.40	27.21	27.07	27.00	26.52
B8	27.10	27.21	27.09	26.63	26.81
B9	27.75	27.47	27.41	26.35	26.10
Mean	27.41	27.31	27.28	26.61	26.44

Fig. 5.1. Graphical and tabular overview of gravimetric water contents (%) in each layer of all four samples tested

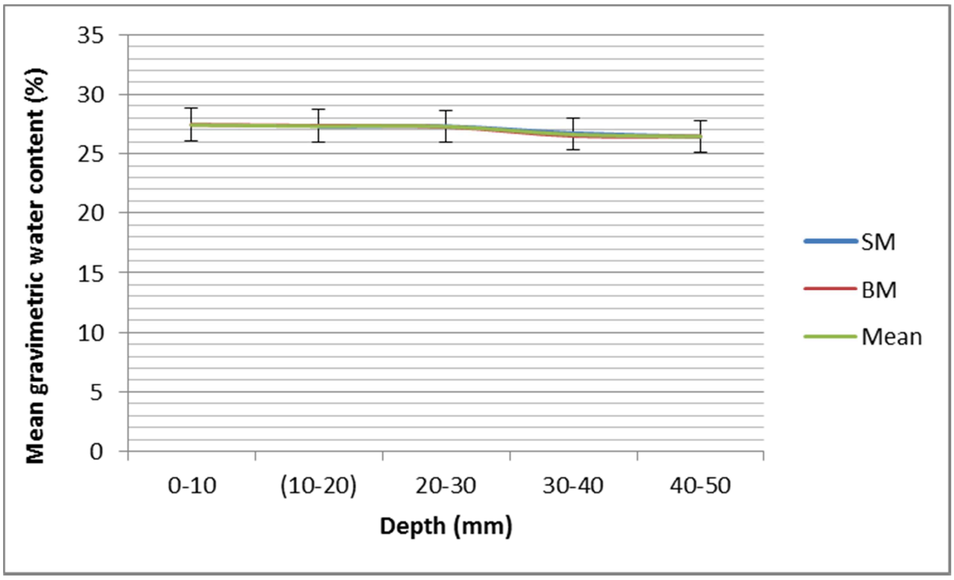
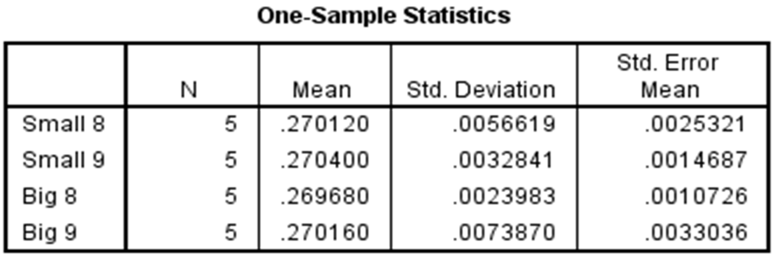


Fig. 5.2. Curve of layer's mean gravimetric water content (%) (SM = small samples, BM = big samples, Mean = all samples)

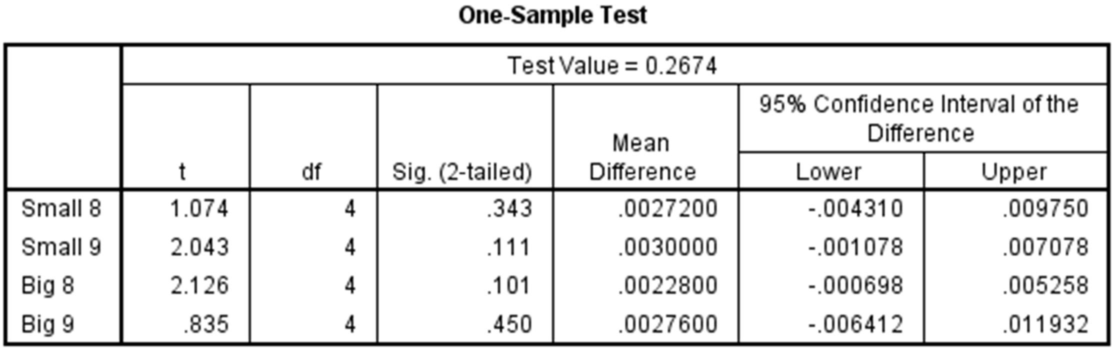
Table 5.3. Mean, standard deviation and mean standard error of gravimetric moisture contents for each core sample, taken over all five layers



One-Sample Statistics

	N	Mean	Std. Deviation	Std. Error Mean
Small 8	5	.270120	.0056619	.0025321
Small 9	5	.270400	.0032841	.0014687
Big 8	5	.269680	.0023983	.0010726
Big 9	5	.270160	.0073870	.0033036

Table 5. 4. t-test for moisture distributions through the sample columns



One-Sample Test

	Test Value = 0.2674					
					95% Confidence Interval of the Difference	
	t	df	Sig. (2-tailed)	Mean Difference	Lower	Upper
Small 8	1.074	4	.343	.0027200	-.004310	.009750
Small 9	2.043	4	.111	.0030000	-.001078	.007078
Big 8	2.126	4	.101	.0022800	-.000698	.005258
Big 9	.835	4	.450	.0027600	-.006412	.011932

*Critical t-value (from the table) is 2.78 at 4 df and 95% confidence interval

**α=0.05 for 95% confidence interval

5.2 Soil Water Retention Curve

Data for soil water retention curves development and evaluation were measured in the laboratory using sand tank (0, 5, 22, 40, 55 and 70 cm) pressure/tension and pressure plate apparatus for 2345 cm of pressure from two sizes of core samples (100 cm^3 and 250 cm^3) and 7 replicates for each. Mass of samples at equilibrium was taken for each applied pressure and volumetric water content for each sample was calculated from measured mass the soil sample and volume of the ring.

Table 5.5. Masses of soil samples with rings, geotextile and rubber bands at different pressure heads (M_s = saturated soil mass), M_r = tare, M_o = dry soil mass)

Sample	**Mass of soil + M_r (g) at pressure head (cm)**							**Mass (g)**		
	0	5	22	40	55	70	2345	M_s+ M_r	M_o+ M_r	M_r
S1	284.19	284.19	280.71	280.07	279.30	278.76	245.84	284.19	245.07	96.26
S2	284.48	284.48	280.35	279.61	278.56	278.08	245.58	284.48	244.72	96.50
S3	284.85	284.85	279.54	279.10	278.21	277.67	246.54	284.85	245.05	96.91
S4	285.67	285.67	281.80	281.04	280.06	279.53	NM	285.67	246.04	97.05
S5	284.03	284.03	283.88	283.67	283.19	282.82	NM	284.03	245.52	97.14
S6	283.13	283.13	277.47	276.51	275.80	275.26	244.14	283.13	243.35	95.73
S7	285.10	285.10	279.16	278.79	277.99	277.00	NM	285.10	245.28	96.60
B1	676.75	676.75	659.92	658.56	655.72	654.36	579.62	676.75	576.41	206.59
B2	674.98	674.98	656.74	655.68	653.29	651.78	579.31	674.98	576.89	207.02
B3	675.20	675.20	658.68	657.60	655.41	654.46	NM	675.20	575.95	205.93
B4	676.52	676.52	669.53	668.15	666.24	665.19	NM	676.52	577.00	206.05
B5	678.49	678.49	664.01	662.83	659.87	659.07	NM	678.49	579.36	209.27
B6	675.83	675.83	663.01	661.54	659.38	657.94	579.02	675.83	576.42	206.41
B7	678.51	678.51	668.84	667.74	665.39	664.45	580.54	678.51	577.89	207.33

*NM for Not Measured, when there was not enough space in the pressure plate apparatus (because of the time limit for the work, as SWRC determination was time taking).

Gross masses in table 5.5 have to be reduced to a common base in order to make the data from different samplers comparable. This is achieved by subtracting the corresponding values of M_r (mass of ring + geotextile + rubber bund) to get the mass of soil with water or by subtracting the value of oven-dry soil with M_r from the gross mass (mass of soil including water and M_r), which gives us the mass (g) or volume (cm^3) of the retained water in each ring at each applied pressure head, see table.5.6.

Table 5.6. Mass of water (g) retained at different applied pressure head (cm)

Sample	Mass of water (g) retained at pressure head (cm)						
	0	5	22	40	55	70	2345
S1	39.12	39.12	35.64	35.00	34.23	33.69	0.77
S2	39.76	39.76	35.63	34.89	33.84	33.36	0.86
S3	39.80	39.8	34.49	34.05	33.16	32.62	1.49
S4	39.63	39.63	35.76	35.00	34.02	33.49	NM
S5	38.51	38.51	38.36	38.15	37.67	37.3	NM
S6	39.78	39.78	34.12	33.16	32.45	31.91	0.79
S7	39.82	39.82	33.88	33.51	32.71	31.72	NM
B1	100.34	100.34	83.51	82.15	79.31	77.95	3.21
B2	98.09	98.09	79.85	78.79	76.40	74.89	2.42
B3	99.25	99.25	82.73	81.65	79.46	78.51	NM
B4	99.52	99.52	92.53	91.15	89.24	88.19	NM
B5	99.13	99.13	84.65	83.47	80.51	79.71	NM
B6	99.41	99.41	86.59	85.12	82.96	81.52	2.6
B7	100.62	100.62	90.95	89.85	87.50	86.56	2.65

Table 5.7. Calculated bulk density (ρ_b), gravimetric (ω) and volumetric (θ) water content, porosity (P) and degree of saturation (S) of the samples at saturation

Sample	**Volume of ring (cm^3)**	**Mw (g)**	**Mo (g)**	**ρ_b (g/cm^3)**	**θ (%)**	**ω (g/g)**	**P (%)**	**S (%)**
S1	100	39.12	148.81	1.48	39.12	0.2629	44.15	88.61
S2	100	39.76	148.22	1.48	39.76	0.2682	44.15	90.05
S3	100	39.8	148.14	1.48	39.8	0.2687	44.15	90.15
S4	100	39.63	148.99	1.49	39.63	0.266	43.77	90.53
S5	100	38.51	148.38	1.48	38.51	0.2595	44.15	87.22
S6	100	39.78	147.62	1.48	39.78	0.2695	44.15	90.10
S7	100	39.82	148.68	1.49	39.82	0.2678	43.77	90.97
B1	250	100.34	369.82	1.48	40.14	0.2713	44.15	90.92
B2	250	98.09	369.87	1.48	39.24	0.2652	44.15	88.88
B3	250	99.25	370.02	1.48	39.70	0.2682	44.15	89.92
B4	250	99.52	370.95	1.48	39.81	0.2683	44.15	90.17
B5	250	99.13	370.09	1.48	39.65	0.2679	44.15	89.81
B6	250	99.41	370.01	1.48	39.76	0.2687	44.15	90.05
B7	250	100.62	370.56	1.48	40.25	0.2715	44.15	91.16
Average				1.48	39.64	0.2674	44.15	89.78

Once the volume or mass of water retained in each sample for a given pressure head is known, see table. 5.6, volumetric or gravimetric water content ($cm^3.cm^{-3}$ or $g.g^{-1}$) for each core sample can be calculated, using equation (4) and (8), respectively. Gravimetric water content (g/g) for the experiment was calculated by dividing the mass of retained water at each applied pressure head by the corresponding value of oven-dry sample mass, while volumetric water content ($cm^3.cm^{-3}$ or %) was calculated from the volume of water retained at each applied pressure head and the volume of the corresponding rings; $100cm^3$ or $250cm^3$, see table 5.8 and 5.9. In these tables and the previous ones, the missing values for the samples to which the pressure was not applied and hence no water content was obtained under 2345 cm pressure head, are marked as NM (for "not measured") and the mean values are calculated from the measured values only.

Table 5.8. Volumetric water content ($cm^3.cm^{-3}$) for small core samples at different applied pressure heads

Sample		**Pressure head (cm)**						
		0	5	22	40	55	70	2345
Volumetric water content ($cm^3.cm^{-3}$)	S1	0.3912	0.3912	0.3564	0.3500	0.3423	0.3369	0.0077
	S2	0.3976	0.3976	0.3563	0.3489	0.3384	0.3336	0.0086
	S3	0.3980	0.3980	0.3449	0.3405	0.3316	0.3262	0.0149
	S4	0.3963	0.3963	0.3576	0.3500	0.3402	0.3349	NM
	S5	0.3851	0.3851	0.3836	0.3815	0.3767	0.3730	NM
	S6	0.3978	0.3978	0.3412	0.3316	0.3245	0.3191	0.0079
	S7	0.3982	0.3982	0.3388	0.3351	0.3271	0.3172	NM
	Mean	0.3949	0.3949	0.3541	0.3482	0.3401	0.3344	0.0098

Water contents in each ring for different applied pressures is presented in table 5.8 and fig. 5.3 for the small core samplers and in table.5.9 and fig. 5.3 for the bigger ones. Water contents for each type of the core samples, together with 95% confidence intervals, are presented in fig. 5.3 for the small core samplers and in fig. 5.4 for the big ones, to judge the uniformity of the data. In the small core samplers' graph, see fig. 5.3, the value from core sample number 5, S5, is out of the mean range for 95% confidence interval, while in the bigger core samplers' graph, see fig. 5.4, the value from core sampler number 4, B4, is out of the range. These values were out of the 95% confidence interval for 22 cm applied pressure onwards, but they were in the range for zero and 5 cm applied pressure, at which no outflow was recorded. These irregularities might happen due to fungal growth which could block the flow of water in those samples, or due to more compaction, especially in the case of the smaller sample, S5, as it had the lowest saturated water content from the group. As they might affect the final result, and to be on the safer side, they were excluded from the final comparison. The mean values in table 5.10 do include them, but the validated means to be used in further comparisons, see table 5.11, are only taken over the rest of the core samples.

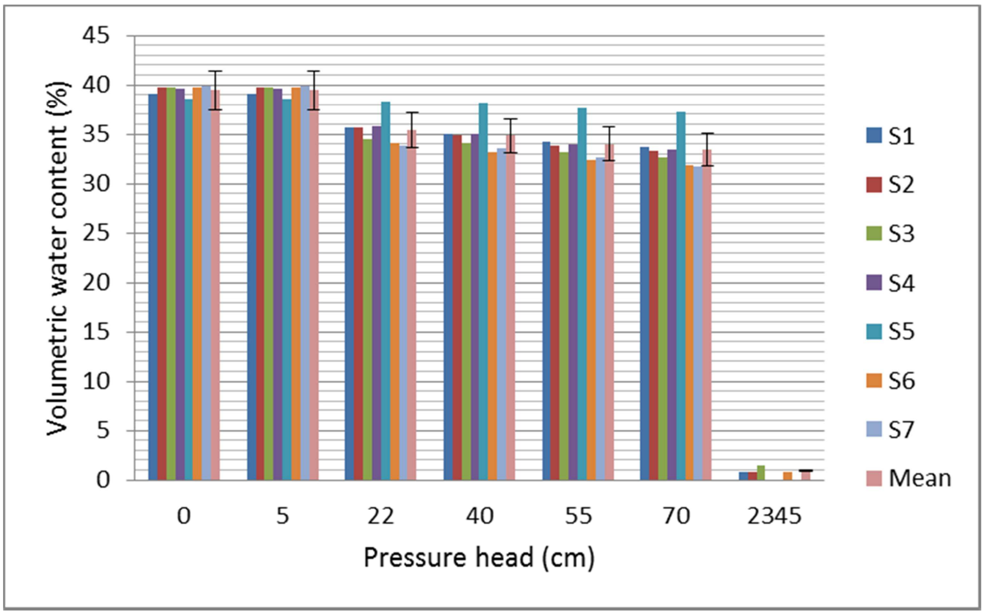


Fig. 5.3. Graph of volumetric water content (%) at different applied pressure heads for small core samplers

Table 5.9. Volumetric water content ($cm^3.cm^{-3}$) for bigger core samplers at different applied pressure heads

Sample		**Pressure head (cm)**						
		0	5	22	40	55	70	2345
Volumetric water content ($cm^3.cm^{-3}$)	B1	0.4014	0.4014	0.3340	0.3286	0.3172	0.3118	0.0128
	B2	0.3924	0.3924	0.3194	0.3152	0.3056	0.2996	0.0097
	B3	0.3970	0.3970	0.3309	0.3266	0.3178	0.3140	NM
	B4	0.3981	0.3981	0.3701	0.3646	0.3570	0.3528	NM
	B5	0.3965	0.3965	0.3386	0.3339	0.3220	0.3188	NM
	B6	0.3976	0.3976	0.3464	0.3405	0.3318	0.3261	0.0104
	B7	0.4025	0.4025	0.3638	0.3594	0.3500	0.3462	0.0106
	Mean	0.3979	0.3979	0.3433	0.3384	0.3288	0.3242	0.0109

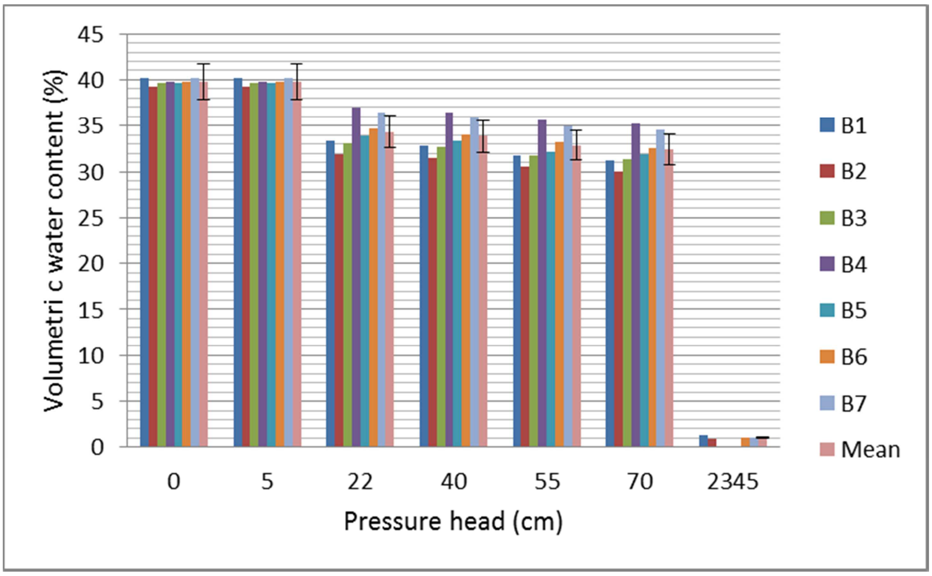


Fig. 5.4. Graph of volumetric water content (%) at different applied pressure heads for bigger core samplers

Table 5.10. Mean volumetric water contents (cm^3.cm^{-3}) at different applied pressure heads for all small (SMA) and bigger (BMA) core samples

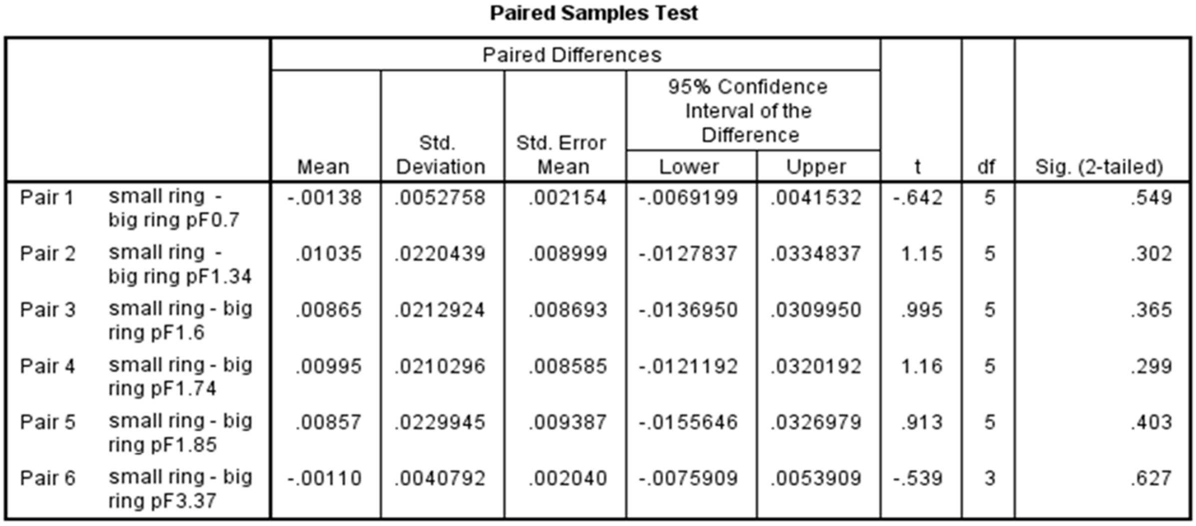
Sample		**pressure head (cm)**						
		0	5	22	40	55	70	2345
θ (cm^3.cm^{-3})	SMA	0.3949	0.3949	0.3541	0.3482	0.3401	0.3344	0.0098
	BMA	0.3979	0.3979	0.3433	0.3384	0.3288	0.3242	0.0109
	MeanA	0.3964	0.3964	0.3487	0.3433	0.3345	0.3293	0.0103

Table 5.11. Validated mean volumetric water contents (cm^3.cm^{-3}) and their differences at different applied pressure heads taken over all small (SMV) and bigger (BMV) samples, except for the out-of-range values

Sample		**Pressure Head (cm)**						
		0	5	22	40	55	70	2345
θ (cm^3.cm^{-3})	SMV	0.3965	0.3965	0.3492	0.3427	0.3340	0.3280	0.0098
	BMV	0.3979	0.3979	0.3389	0.3340	0.3241	0.3194	0.0109
	MeanV	0.3972	0.3972	0.3440	0.3384	0.3291	0.3237	0.0103
SMV-BMV		-0.0014	-0.0014	0.0103	0.0087	0.0099	0.0086	-0.0011

The validated means of measured volumetric water contents ($cm^3.cm^{-3}$), see table 5.11, were fitted to different models, using RETC computer software program. The measured values were fitted to the Brooks-Corey, van Genuchten (with m and n optimized independently, m=1-1/n and m=1-2/n) and log-normal distribution models, see table 5.13.

Table 5.12. Paired (small vs. big core samples) t-test for volumetric water contents ($cm^3.cm^{-3}$) at different applied pressures, using SPSS computer program



Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	small ring - big ring pF0.7	-.00138	.0052758	.002154	-.0069199	.0041532	-.642	5	.549
Pair 2	small ring - big ring pF1.34	.01035	.0220439	.008999	-.0127837	.0334837	1.15	5	.302
Pair 3	small ring - big ring pF1.6	.00865	.0212924	.008693	-.0136950	.0309950	.995	5	.365
Pair 4	small ring - big ring pF1.74	.00995	.0210296	.008585	-.0121192	.0320192	1.16	5	.299
Pair 5	small ring - big ring pF1.85	.00857	.0229945	.009387	-.0155646	.0326979	.913	5	.403
Pair 6	small ring - big ring pF3.37	-.00110	.0040792	.002040	-.0075909	.0053909	-.539	3	.627

Significance (2-tailed) is greater than 0.05, and hence there is no statistically significant difference between the mean water content retained in small core samples and that retained in big core samples. The t critical from the t-table is 2.57 at 5 degrees of freedom and 3.18 at 3 degrees of freedom for the 95% confidence interval. However, p-values comparison is enough for a two tailed t-test. As p-value > 0.05 and t-critical > t-observed, there is no statistically significant difference between the two means.(see Discussion).

Table 5.13. Fitted soil water retention curve parameters from different models using RETC software

Type of Model	**Ring size**	**θ_r**	**θ_s**	**α**	**n**	**λ, *m***	**R^2**	**SSQ**
		($cm^3.cm^{-3}$)		**(1/cm)**	**(-)**	**(-)**	**(%)**	**(10^{-4})**
BC	SM	0	0.3638	0.0158	-	**λ** =0.9997	96.6	37
	BM	0	0.3586	0.0161	-	**λ** =0.9619	95	53
VG m, n	SM	0	0.3932	0.0013	1.005	m=2.43	99.5	5.6
	BM	0	0.3935	0.002	1.005	m=1.876	99.12	9.4
VG m=1-1/n	SM	0	0.3832	0.01	1.962	m=0.4903*	98.7	14
	BM	0	0.383	0.0115	1.866	m=0.4641*	98.1	20
VG m=1-2/n	SM	0	0.3779	0.0133	2.9	m=0.3104*	98.2	20
	BM	0	0.3763	0.0149	2.82	m=0.2909*	97.3	28
Log-normal distribution	SM	0	0.3888	233.2	1.375	-	99.1	9.6
	BM	0	0.3907	216.32	1.488	-	98.8	12

*shows that m is calculated from n

-The programme automatically changed to fit with θ_r to 0.0 when the value is less than 0.001

The measured data were best fitted to VG model with m and n optimized independently and log-normal distribution. They were less successfully fitted to BC, VG (m= 1-1/n) and VG (m= 1-2/n). They were 99.5% fitted to the VG with m and n optimized independently with the sum of square residuals (SSQ) = 0.00056 for the mean of small core sample and 99.12% fitted with the sum of square residuals (SSQ) = 0.00094 for the mean of big core samples, while to the log-normal distribution they were fitted 99.1% with SSQ = 0.00096 for the mean of the small core samples and 98.8% with SSQ = 0.0012 for the mean of the big core samples. However, they fitted least to BC. They fitted 96.9% to BC with SQQ = 0.0037 for the mean of the small core samples and 95% with SQQ = 0.0053 for the mean of the big core samples. Hence, the fitted data of validated means for small and bigger core samplers according to VG (m, n) and log-normal distribution were used for further analysis.

Table 5.14. Measured and fitted volumetric water contents using RETC computer program for small (BM) and bigger (BM) samples

Ψ_m (pF)	**θ($cm^3.cm^{-3}$) measured**		**θ($cm^3.cm^{-3}$) fitted**			
			VG		**Log-normal distribution**	
			m, n			
	SM	BM	SM	BM	SM	BM
0	0.3965	0.3979	0.3932	0.3935	0.3888	0.3907
0.7	0.3965	0.3979	0.3872	0.3863	0.3878	0.3884
1.34	0.3492	0.3389	0.3675	0.363	0.3721	0.3663
1.6	0.3427	0.334	0.3481	0.3406	0.35	0.3405
1.74	0.334	0.3241	0.3329	0.3234	0.3318	0.3208
1.85	0.328	0.3194	0.3187	0.3075	0.3147	0.3031
3.37	0.0098	0.0109	0.0129	0.0146	0.0181	0.0213

6. Discussion

6.1 Moisture distribution through the sample column at saturation

Gravimetric water contents for individual layers of both big and small core samples were taken to observe the moisture distribution over the core sample height from the top downwards, see table 5.2. The results show some variation. The moisture contents tend to decrease downwards, see table 5.2 and fig. 5.2. The differences may arise from compaction during the sample packing/preparation. While packing the sample at the upper layer, the lower layers get additional pressure/stress as the lowest layer was filled first and the upper layer last. The difference may also be due to evaporation during the taking of disturbed samples of saturated soil from each layer, as they were taken in downward order; the top sample first and the bottom one last. However, the moisture contents for all layers of the core samples fall within the range of 95% confidence interval, see fig. 5.1.

Furthermore, in order to prove the uniformity of moisture distribution and homogeneity of soil bulk density throughout the soil column, gravimetric water contents (g/g) of each layer for both types of the rings were tested using t-test in SPSS software program, see table 5.4. As all p-values are greater than 0.05, there is no statistically significant difference between the mean of gravimetric water content of samples for soil water retention curves and the mean of gravimetric water content (g/g) of layers of both small and big core samples. The test value 0.2674 (g/g) was taken from the mean gravimetric water content of samples for soil water retention curves determination. The mean value for two types of core samples in the group for moisture distribution are therefore the same as the mean value for the other group of samples used for the soil water retention curves. Moisture distribution within the soil sample column is virtually uniform and the mean difference between the two groups (the first group being used for moisture distribution evaluation and the second group for soil water retention curve analysis) is statistically insignificant. This demonstrates that there is sufficient uniformity and homogeneity of the packed samples.

Average recommended porosity is 37.3 % for the sand used for the study, see Appendix B; however, the calculated average porosity from average bulk density in table 5.7 and particle density (2.65 g/cm^3), see Appendix B, is 44.15% and the average saturated porosity for the sample was 39.64%. Hence, the degree of saturation was 89.78%, see table 5.7. According to van Genuchten (1991), saturated moisture content θ_s can be 5 to 10% less than porosity due to entrapped or dissolved air. However, Mihalikova (2012) shows that the degree of saturation for a saturated loamy sand is 86%.

6.2 Soil water retention curves comparison

Soil water content at equilibrium with respective applied pressure/suction head over the measured range (0, 5, 22, 40, 55, 70 and 2345 cm) for the small and bigger core samples did not show any visible difference, see tables 5.2.4 and 5.2.5, for this uniformly distributed sand. Rather the curves for both types of cores were overlaying one another, see the pF curve for all valid values from small and bigger core samples in fig. 6.1. However, the means calculated from measured data on the one hand and the fitted data on the other hand for both types of core samples were not the same, see tables 5.11.

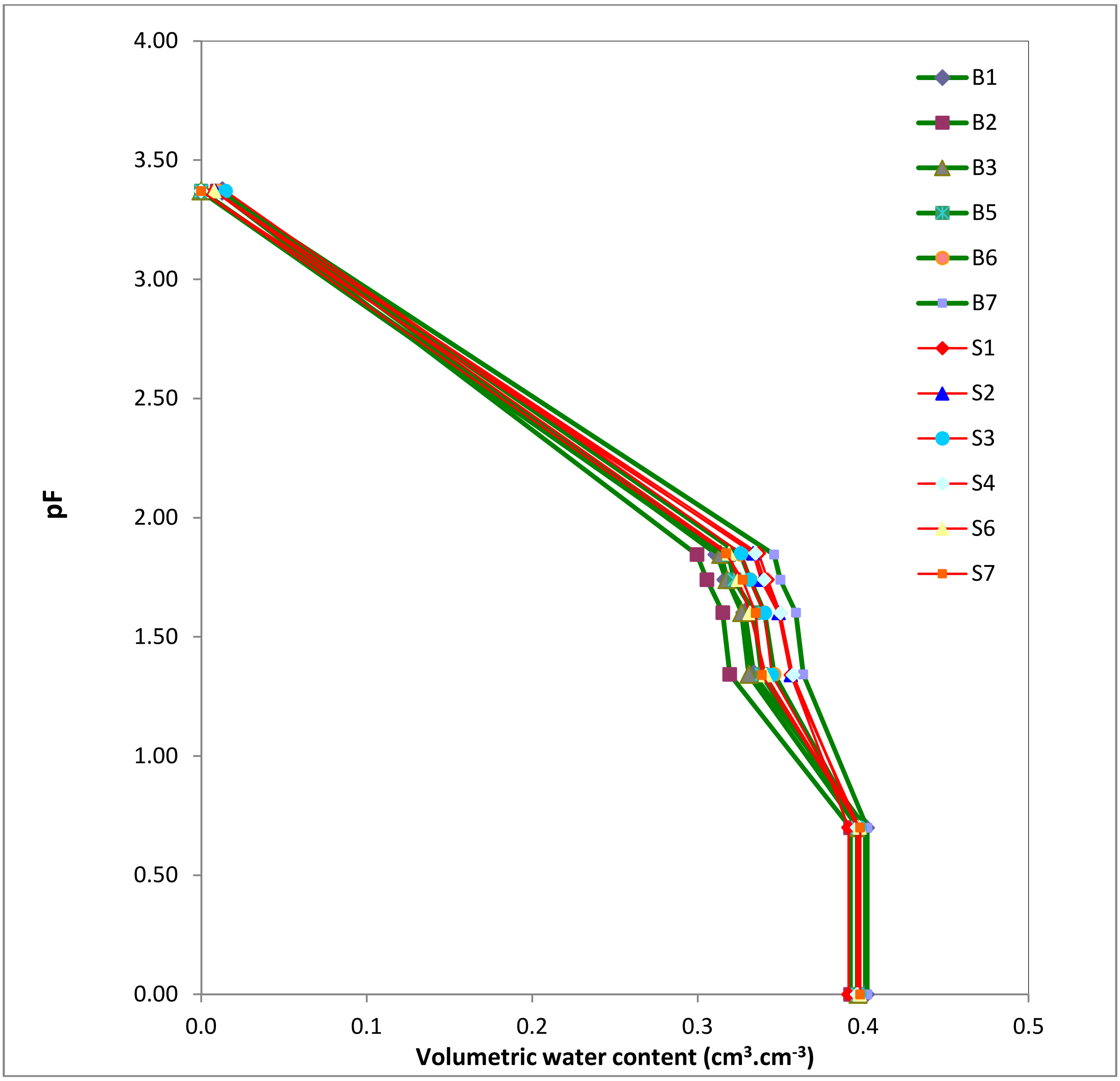


Fig. 6.1. pF curves made of validated measured values for all core samples

Calculated mean water contents for both types of the core samples were almost the same at saturation with 0.0014 cm^3/cm^3 difference, which is very low and insignificant compared to the mean value over both types of the rings, which was 0.3972 cm^3/cm^3, see table 5.11. However, the difference in the mean water content between the two types of rings increased to the maximum value 0.0103 cm^3/cm^3 at 22 cm (or 1.34 pF), while the mean value over both ring types decreased to 0.3440 cm^3/cm^3. For higher pressure heads, both the validated mean volumetric water content over the two ring types and their mean difference decreased together. From t-test using SPPS program, see table 5.12, the difference between the mean values for small and big core samples over the applied range of pressure heads was statistically insignificant. However, it is very important to compare the entire curves of mean volumetric water content vs. matric head, as soil water retention curve is a continuous function, rather than discrete points.

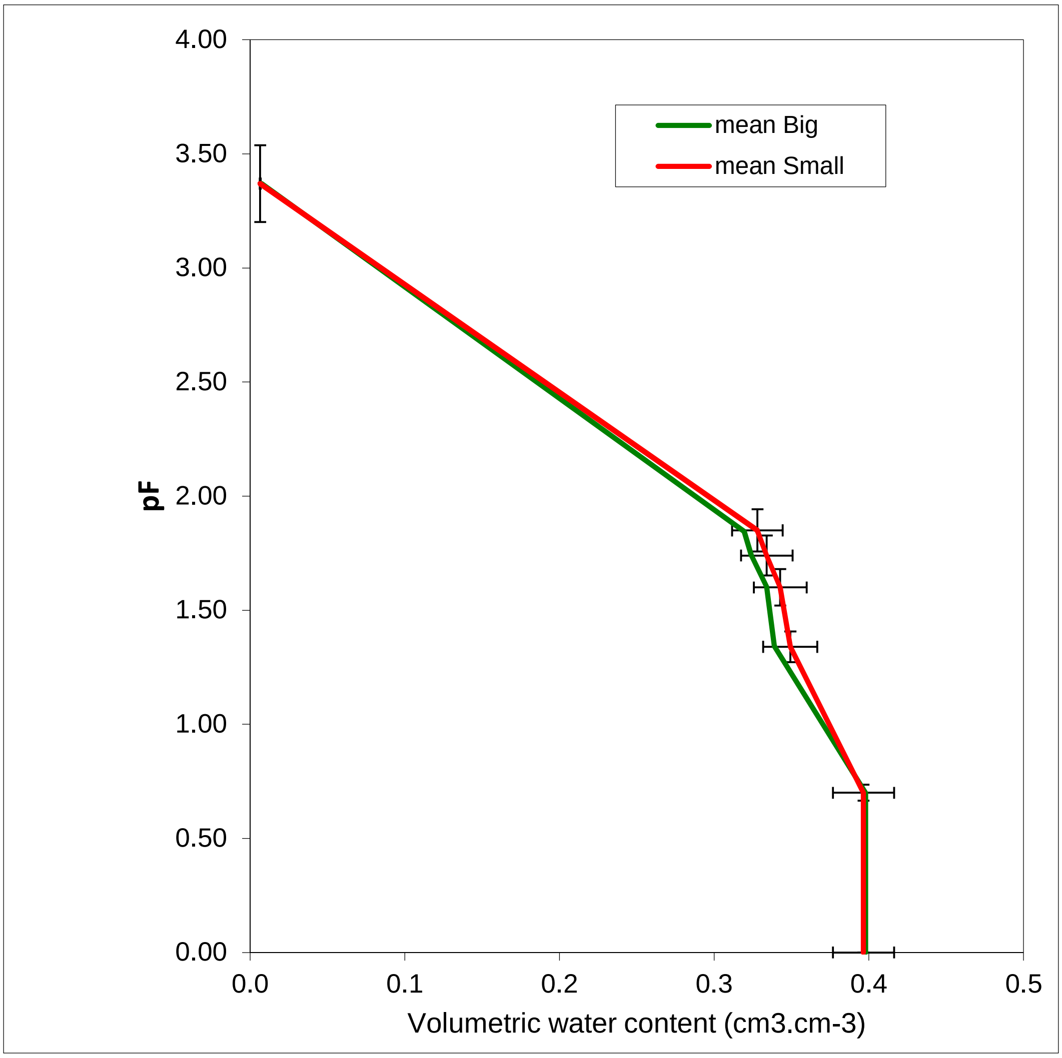


Fig. 6.2. pF curves made of validated means for the two types of samples with 95% confidence intervals

The pF curves made of the mean volumetric water content for the two core sample sizes were plotted see fig. 6.2, together with 95% confidence intervals. The curves were plotted from the measured data over the range of applied pressures only. For the points at which no outflow was recorded (0 and 0.7 pF), the two curves overlap; while for those points at which some outflow was recorded, there is a difference in means, signifying that the mean over small core samples retain some more water than the mean over the big ones, except for the pF 3.37 /2345cm. Even though there is this difference, it is not statistically significant at 95% confidence level, see fig. 6.2.

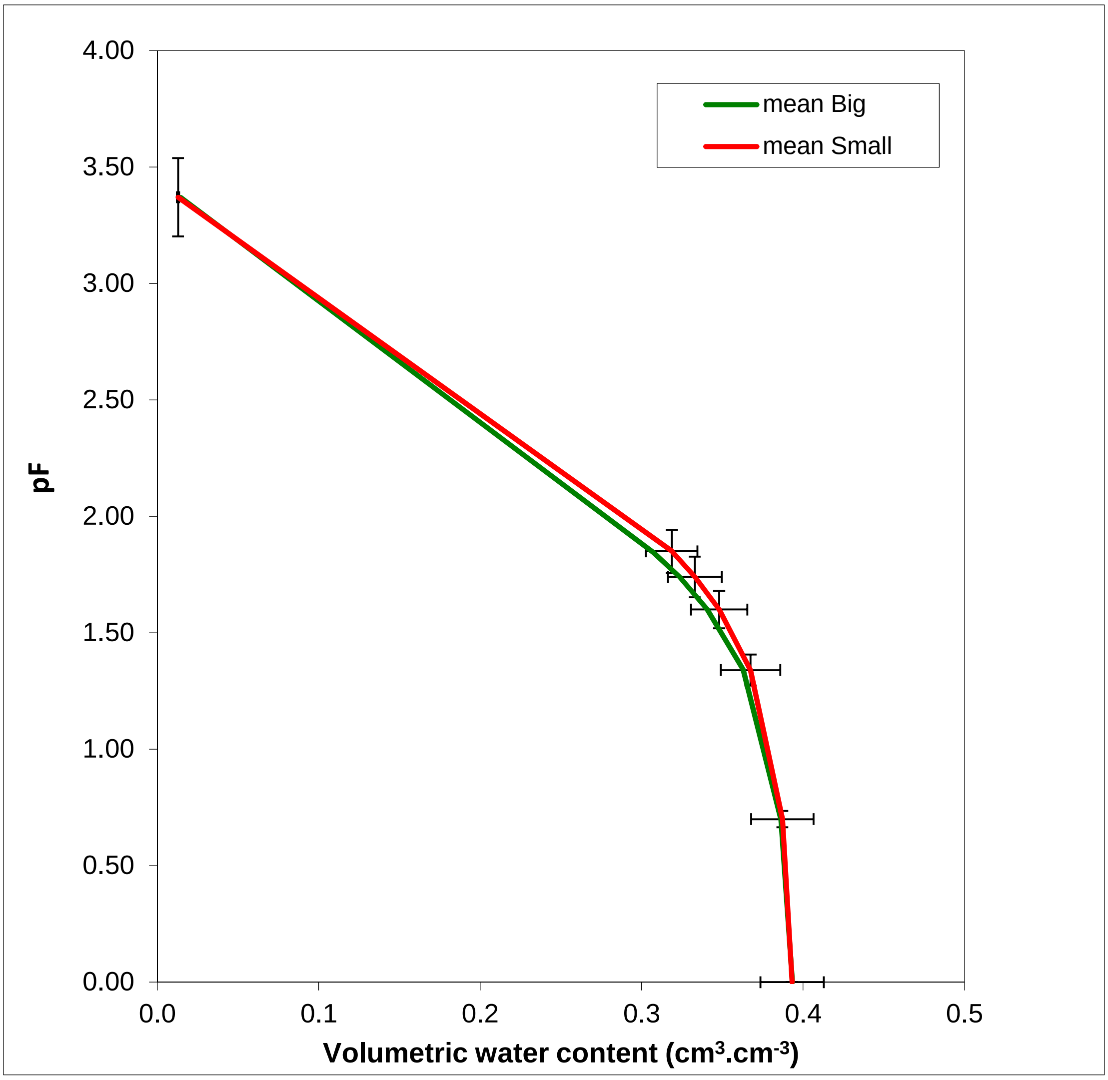


Fig. 6.3. Fitted pF curves using the VG model for validated means of the two sample types with 95% confidence intervals

Smooth soil water retention curves from fitted data were also evaluated. Measured data were 99.5% fitted to the VG with m and n optimized independently with the sum of square residuals (SSQ) = 0.00056 for the mean of small core sample and 99.12% fitted with the sum of square residuals (SSQ) = 0.00094 for the mean of big core samples, while to the log-normal distribution they were fitted 99.1% with SSQ = 0.00096 for the mean of the small core samples and 98.8% with SSQ = 0.0012 for the mean of the big core samples, see table 5.13.

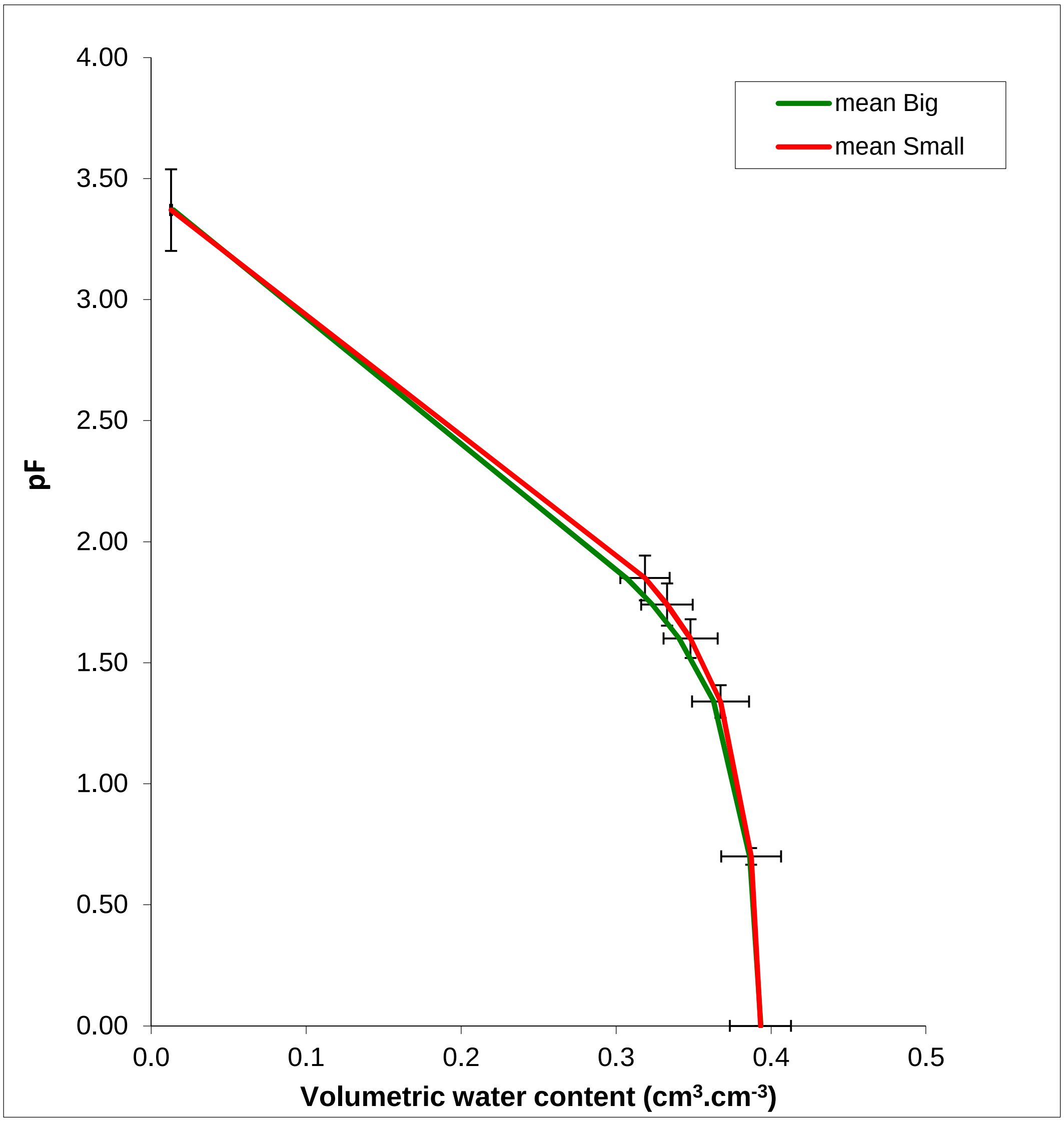


Fig. 6.4. Fitted pF curves using the log-normal distribution for validated means of the two sample types with 95% confidence interval

Soil water retention curves were developed from the fitted data table 5.14 for both small and big core samples. Developed soil water retention curves using VG (Fig. 6.3) and log-normal distribution fig. 6.4 for 95% confidence interval shows no significant difference for the small and big core samples.

Soil water retention curves from small (100 cm^3) and big (250 cm^3) core samples do not show statistically significant difference between their mean. According to Miyazaki (2006), a soil water retention curve is the characteristics of each soil and the difference is primarily due to pore size distribution among soils. However, Dawson et al. (2008) argued that the curve is not the sole function of a given soil but varies with temperature, pore water chemistry and pressure, and hence, it is something of a misnomer to say the curve is the characteristics of each soil.

7. Conclusions and Recommendations

7.1 Conclusions

Soil water retention curves were determined with two commonly used core sample sizes to evaluate the effect of the core sample size on the soil water retention curves. The study was performed using silica sand with uniform and narrow-range particle size distribution, compared to natural soils. The sample was packed into the rings manually. The moisture distribution within the packed samples was analyzed after saturation for uniformity and the mean saturated gravimetric water content of the group of samples used for the moisture distribution analysis was compared with that of the group of samples used for the soil water retention curves evaluation. The results show that the differences in moisture contents between different groups of rings as well as the variability of moisture distribution along the sample column were statistically insignificant and, hence, the analysis of soil water retention curves for differently sized core samples was valid

The differences in soil water retention curves for two commonly used core sample sizes (100 cm^3 and 250 cm^3) of homogeneous silica sand over the applied range of pressure heads (0 to 2345 cm) were statistically insignificant. Therefore, the hypothesis that there is no significant difference between soil water retention curves of this particular homogeneous material for these volume ranges due to core sample sizes is acceptable.

7.2 Recommendations

This study was done on uniformly packed soil samples of silica sand in relatively small ring sizes with volume 100 cm^3 and 250 cm^3 for relatively small portion of the soil water retention curve. According to previous experiments of other authors (see the Literature review), soil can retain water up to 10^6 cm applied pressure; but in this work maximum pressure head applied was 2345 cm. The silica sand used had a relatively uniform particle size distribution, in contrast to natural soils which have a very wide range of particle size distribution from very fine clay to very coarse sand, with gravel and stones often found within field soil samples. Moreover, the field/undisturbed soils vary in their bulk density, which influences their respective porosity. Hence, it may not be possible to get a representative elementary volume using those rings of the sizes that were used in this work.

Therefore, the way forward is to extend the study with experimentation which focuses on the use of field/undisturbed soils with bigger core samplers and a broader scale of sample sizes over the whole workable range of soil water retention curves with many points.

8. References

Ali, M.H. 2010. Fundamentals of Irrigation and On-farm Water management. Springer. New York, USA. p. 560. ISBN: 978-1-4419-6334-5.

Anderson, S., Schaeltz, R.J. 2005. Soils Genesis and Geomorphology. Cambridge University Press. Cambridge, UK. p. 817. ISBN: 978-0-521-81201-6.

Assouline, S. 2006. Modeling the Relationship between Soil Bulk Density and the Water Retention Curve. *Vadose Zone Journal.* 5. 554–563.

Behari, J. 2005. Microwave Dielectric Behaviour of Wet Soil. Anamaya Publishers. New Delhi, India. p. 164. ISBN: 1-4020-3271-4.

Brady, N.C., Weil, R.R. 2004. Elements of the Nature and Properties of Soils. Prentice Hall. New Jersey, USA. p. 624. ISBN: 978-0-1350-1433-2.

Brooks, R.H., Corey, A.T. 1964. Hydraulic Properties of Porous Media. *Hydrology Papers*, Colorado State University.

Bross, K., Baldock, J.A. 2012. Soil Organic Matter. In: Sumner, M.E., Huang, P.M., Li, Y. (eds.). Handbook of Soil Sciences: Properties and Processes. CRC Press. Florida, USA. p. 11-1. ISBN: 978-1-4398-0305-9.

Campbell, G.S. 1994. Soil Physics with Basic Transport Models for Soil-Plant Systems. Elsevier Science B.V. New York, USA. p. 150. ISBN: 0-444-40882-7.

Chan, T.P., Govindaraju, R.S. 2004. Estimating Soil Water Retention Curve from Particle-Size Distribution Data Based on Polydisperse Sphere Systems. *Vadose Zone Journal.* 3. 1443–1454.

Cresswell, H.P., Green, T.W., McKenzie, N.J. 2006. The Adequacy of Pressure Plate Apparatus for Determining Soil Water Retention. *Soil Science Society of America Journal*. 72. 41-49.

Dashtaki, G.S., Homaee, M., Khodaverdiloo, H. 2010. Derivation and Validation of Pedotransfer Functions for Estimating soil Water Retention Curve Using a Variety of Soil Data, Soil Use and Management. *Soil Use and Management.* 26. 68–74.

Dawson, A., Erlingson, S., Brencic, M. 2008. Water Flow Theory for Saturated and Unsaturated Pavement Material. In: Dawson, A. (ed.). Water in Road Structures: Movement and Drainage Effects (Geotechnical, Geological and Earthquake

Engineering). Springer Science + Business Media B.V. UK. p. 23-44. ISBN: 978-1-4020-8561-1.

Eijkelkamp. Eijkelkamp Agrisearch Equipment BV. Available at <http://en.eijkelkamp.com> Accessed on January 21, 2012.

Fooladmand, H.R. 2011. Pedotransfer Functions for Point Estimation of Soil Moisture Characteristic Curve in Some Iranian Soils. *African Journal of Agricultural Research*. 6(6). 1586-1591.

Fredlund, D.G. 2002. Use of Soil–Water Characteristic Curves in the Implementation of Unsaturated Soil Mechanics. UNSAT 2002 *Proceedings. International Conference on Unsaturated Soils*. Recife, Brazil. March 10-13.

Fredlund, D.G., Rahardjo, H. 1993. Soil Mechanics for Unsaturated Soils. John Wiley & Sons. New York, USA. p. 544. ISBN: 978-0-4718-5008-3.

Fredlund, D.G., Rahardjo, H., Leong, E.C., Charless, W.W.Ng. 2001. Suggestions and Recommendations for the Interpretations of Soil-Water Characteristics Curve. *Proceedings of the 14th Southeast Asian Geotechnical Conference*. 1. 503-508. Hong Kong. December 10-14.

Fredlund, D.G., Wilson, G.W., Barbour, S.L. 2001. Unsaturated Soil Mechanics and Property Assessment. In: Rowe, R.K. (ed.). Geotechnical and Geoenviromental Engineering Handbook. Kluwer Academic Publishers. Massachusetts, USA. p 107-146. ISBN: 0-7923-8613-2.

Fredlund, D.G., Xing, A. 1994. Equations for Soil-Water Characteristics Curve. *Canadian Geotechnical Journal*. 31. 521-532.

Fredlund, M.D., Fredlund, D.G., Wilson, G.W. 1997. Prediction of the Soil-Water Characteristic Curve from Grain-Size Distribution and Volume-Mass Properties. 3rd Brazilian Symposium on Unsaturated Soils. 1. 13-23, Rio de Janeiro, Brazil.

Fredlund, M.D., Sillers, W.S., Fredlund, D.G., Wilson, G.W. 1996. Design of a Knowledge-Based System for Unsaturated Soil Properties. In: Wilson, G.W., Barbour, S.L., Clifton, A.W. (eds.). The Emergence of Unsaturated Soil Mechanics, Fredlund Volume. National Research Council of Canada. Ottawa, Canada. p. 207-216. ISBN: 0-660-17256-9.

Gardner, W.R. 1958. Some Steady-State Solutions of the Unsaturated Moisture Flow Equation with Application to Evaporation from a Water Table. *Soil Science*. 85. 228-232.

Golder Associates. 2006. Report on Approaches and Methods for Evaluation of Unsaturated Zone Contaminant Transport Processes and Effects on Groundwater: Hydrological Assessment Tools project. Golder Associates Ltd. British Columbia, Canada.

Gorokhovski, V. 2012. Effective Parameters of Hydrological Models. Springer. Georgia, USA. p. 153. ISBN. 978-3-642-23721-8.

Goss, M., Ehlers, W. 2003. Water Dynamics in Plant Production. CABI publishing. Wallingford, UK. p. 273. ISBN: 0-85199-694-9.

Haverkamp, R., Bouraoui, F., Zammit, Ch., Angulo-Jarmillo, R. 1999. Soil Porosity and Moisture Movement in the Unsaturated Zone. In: Delleur, J.W. (ed.). The Handbook of Ground Water Engineering. CRC Press. Florida, USA. P. 5-1 - 5-47. ISBN: 0-8493-2698-2.

Hignett, C., Evett, S.R. 2008. Direct and Surrogate Measures of Soil Water Content. In: Evett, S.R., Heng, L.K., Moutonnet, P., Nguyen, M.L., editors. Field Estimation of Soil Water Content: A Practical Guide to Methods, Instrumentation, and Sensor Technology. IAEA-TCS-30. International Atomic Energy Agency, Vienna, Austria. ISSN 1018-5518. p. 1-22.Hillel, D. 1998. Environmental Soil Physics. Academic Press. New York, USA. p. 771. ISBN: 0-12-348525-8.

Horton, R., Jury, W.A. 2004. Soil physics. John Wiley and Sons. New Jersey, USA. p. 384. ISBN: 978-0-4710-5965-3.

Karvonen, T. 2003. Soil and Groundwater Hydrology. Helsinki, Southern Finland - Finland. Available at <http://www.water.tkk.fi/wr/kurssit/Yhd-12.122/www_book/sgh.htm> Accessed on February 15,2012.

Kastanek, F.J., Nielsen, D.R. 2001. Description of Soil Water Characteristics Using Cubic Spline Interpolation. *Soil Science Society of American Journal*. 65(2). 279–283.

Khanzode, R.M., Fredlund. D.G. and Vanapalli, S.p. 2000. A New Test Procedure to Measure the Soil Water Characteristics Curves Using a Small-Scale Centrifuge. *Asian Conference on Unsaturated Soil (UNSAT-ASIA 2000) from Theory to Practice*. may, 18-20, 2000.

Khlosi, M., Cornelis, W.M., Douaik, A., van Genuchten, M.Th., Gabriels, D. 2008. Performance Evaluation of Models That Describe the Soil Water Retention Curve between Saturation and Oven Dryness. *Vadose Zone Journal*.7. 87–96.

Koorevaar, P., Menelik, G., Dirksen, C. 1999. Elements of Soil Physics. Elsevier Science B.V. Amsterdam. The Netherlands. p. 228. ISBN: 0-444-42242-0.

Kutilek, M., Nielsen, D.R. 1994. Soil Hydrology. GeoEcology textbook. Catena Verlag, Cremlingen-Destedt. p. 370. ISBN: 978-3-9233-8126-5.

Lieth, J.H., Ravij, M. 2008. Soilless Culture: Theory and Practice. Elsevier BV. London, UK. p. 587. ISBN: 978-0-444-52975-6.

Matula, S., Mojrová, M., Špongrová, K. 2007. Estimation of the Soil Water Retention Curve (SWRC) Using Pedotransfer Functions (PTFs). *Soil & Water Research*. 2(4). 113–122.

Miháliková, M. 2011. Pedotransferové funkce pro odhad hydrofykálních vlastností půd. Dissertation. Czech University of Life Sciences Prague. Faculty of Agrobiology Food and Natural Resources. Praha. p 91.

Miller, C.J., ASCE, M., Yesiller, N., ASCE, A.M., Yaldo, K., Merayyan S. 2002. Impact of Soil Type and Compaction Conditions on Soil Water Characteristic. *Journal of Geotechnical and Geoenvironmental Engineering*. 128(9). 733-742.

Miyazaki, Ts. 2006. Water Flow in Soils. CRC Press. Florida, USA. p. 418. ISBN: 978-0-8247-5325-2.

Miller, D.J., Nelson, J.D. 1992. Expansive Soils: Problems and Practice in Foundation and Pavement Engineering. John Wiley and Sons, Inc. USA. p. 288. ISBN: 978-0-4711-8114-5.

Mohammadi, M.H., Vanclooster, M. 2011. Predicting the Soil Moisture Characteristic Curve from Particle Size Distribution with a Simple Conceptual Model. *Vadose Zone Journal*. 10. 594-602.

Morgan, K.T., Parsons, L.R., Wheaton, T.A. 2001. Comparison of Laboratory- and Field-Derived Soil Water Retention Curves for a Fine Sand Soil Using Tensiometric, Resistance and Cpacitance Methods. *Plant and Soil. 234*. 153–157.

Mukherjee, S.K., Biswas, T.D. 2006. Textbook of Soil Science. Tata McGraw-Hill Publishing Company limited. New Delhi, India. p. 433. ISBN: 0-07-462043-6.

Nielsen, D.R., Hopmans, J.W., Kutilek, M., Wendroth, O. 1997. A brief Review of Soil Water, Solute Transport and Regionalized variable Analysis. *Science and Agriculture*. 54. 54-115.

Nimmo, J.R., Herkelrath, W.N., Luna, A.M.L. 2007. Physically Based Estimation of Soil Water Retention from Textural Data: General Framework, New Models, and Streamlined Existing Models. *Vadose Zone Journal*. 6.766–773.

Pan, H., Qing, Y., Pei-yong, L. 2010. Direct and Indirect Measurement of Soil Suction in the Laboratory. *The Electronic Journal of Geotechnical Engineering*. 15. [online]. Available from <http://www.ejge.com/2010/JourTOC15A.htm>. [cit. 2011-10-22]

Péron, H., Hueckel, T., Laloul, L. 2007. An Improved Volume Measurement for Determining Soil Water Retention Curves. *Geotechnical Testing Journal*. 30(1). 100-167.

Peroni, N., Tarantino, A. 2005. Measurement of Osmotic Suction Using the Squeezing Technique. In: Schanz, T. (ed.). Unsaturated Soils: Experimental Studies. Springer *Proceedings in Physics*. 93(2). 159-168.

Prunty, L., Casey, F. X. M. 2002. Soil Water Retention Curve Description Using a Flexible Smooth Function. *Vadose Zone Journal.* 1. 179–185.

Rajkai, K., Kabosa, S., van Genuchten, M.Th. 2004. Estimating the Water Retention Curve from Soil Properties: Comparison of Linear, Nonlinear and Concomitant Variable Methods. *Soil & Tillage Research*. 79. 145–152.

Ramos, T.B., Gonçalves, M.C., Martins, J.C., van Genuchten, M.Th., Pires F.P. 2006. Estimation of Soil Hydraulic Properties from Numerical Inversion of Tension Disk Infiltrometer Data. *Vadose Zone Journal.* 5. 684–696.

Rose, C.W., Marshal, T.J., Holmes, J.W. 1999. Soil Physics. Cambridge University Press. Cambridge, UK. p. 472. ISBN: 978-0-521-45766-1.

Schaap, M.G., Nemes, A., van Genuchten, M.Th. 2004. Comparison of Models for Indirect Estimation of Water Retention and Available Water in Surface Soils. *Vadose Zone Journal.* 3.1455–1463.

Scott, H.D. 2000. Soil Physics. Agricultural and Environmental Applications. Iowa State University Press, Iowa, USA. p. 422. ISBN: 978-0-8138-2087-3.

Shukla, M.K., Lal, R. 2004. Principles of Soil Physics. Marcel Dekker, INC. New York. p. 682. ISBN: 0-3247-5324-0.

Sklopisek Střeleč. Available at <http://www.glassand.eu/GB/index.php?page=katalog> Accessed on September 25, 2011.

Soilmoisture. Soilmoisture Equipment Corp. Available at <http://www.soilmoisture.com/> Accessed on August 08, 2011.

Tuller, M., Or, D. 2003. Retention of Water in Soil and the Soil Water Characterstics Curve. http://www.engr.uconn.edu/environ/envphys/pdf/vadose_pdf/SWC_revised01.pdf.

Vanapalli, S.K., Fredland, M.D. and Sillers, W.S. 1998. The Meaning and Relevance or Residual State of Unsaturated Soils. *51st Canadian Geothechnical Conference*. Edmonton, Canada. October 4-7.

van Genuchten, M. Th. 1980. A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. *Soil Science Society of America Journal*. 44. 892-898.

van Genuchten, M. Th., Leij, F.J., Yates, S.R. 1991. The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils. U.S. Environmental Protection Agency, Oklahoma, USA.

Vaz, C.M.P., Hopmans, .J.W., Macedo, A., Bassoi, L.H., Wildenschild, D. 2002. Soil Water Retention Measurements Using a Combined Tensiometer-Coiled Time Domain Reflectometry Probe. *Soil Science Society of America Journal*. 66. 1752–1759.

Vereecken, H., Weynants, M., Javaux, M., Pachepsky, Y., Schaap, M. G., van Genuchten, M.Th. 2010. Using Pedotransfer Functions to Estimate the van Genuchten–Mualem Soil Hydraulic Properties. *Vadoze Zone Journal*. 9. 795-820.

Walczak, R., Sławiński, C., Witkowska-Walczak, B. 2004. Determination of Water Potential-Moisture Characterstics of Soil Porous Media. Institute of Agrophysics PAS. Lublin, Poland. p. 83. ISBN: 83-87385-93-x.

White, R.E. 2006. Principles and Practice of Soil Science. The Soil as a Natural Resource. Blackwell Publishing. Malden, USA. p. 363. ISBN: 978-0-632-06455-7.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas C. 1999. Development and Use of a Database of Hydraulic Properties of European Soils. *Geoderma*. 90. 169-185.

Wraith, J.M., Or, D. 2002. Soil Water Content and Water Potential Relationships. In: Warrick, A.W. (ed.). Soil Physics Companion. CRC Press. Washington D.C, USA. p. 49-84. ISBN: 0-8493-0837-2.

Zhou, J.,Yu, J. 2005. Influences Affecting the Soil-Water Characteristic Curve. *Journal of Zhejiang University Science* 6A (8). 797-804.

9. Nomenclature, list of abbreviations

9.1 Symbols

a = empirical constant in hyperbola equation for SWRC (-)

b = empirical constant in hyperbola equation for SWRC (-)

C_{Θ} = specific water capacity ($L.T^{2}.M^{-1}$)

e = void ratio (-)

g = acceleration due to gravity ($L.T^{-2}$)

m= empirical constant affecting the shape of SWRC (-)

M_s = mass of oven dry soil (M)

M_w = mass of water (M)

n = empirical constant affecting the shape of SWRC (-)

P = porosity (-)

R = radius of pores/tube (L)

R^2 = Coefficient of determination in fitting measured data to models using RETC

r_b = effective radius of bigger pores/tube (L)

r_s = effective radius of smaller pores/tube (L)

S = degree of saturation (%)

V = volume (L^3)

V_g = Pore space that is occupied by gasses or not occupied by water (L^3)

V_{P} = pore space (L^3)

V_s= volume of solid soil (L^3)

V_t= bulk volume of soil (L^3)

V_w=volume of soil water (L^3)

W_s=mass of saturated soil (M)

W_w= mass of wet soil (M)

α=emperical parameters whose inverse is often mentioned as air entry suction (L^{-1})

β=contact angle between water and soil particles

β_d= contact angle between water and soil particles during drying

β_w= contact angle between water and soil particles during wetting

γ=Liquid air surface tension in soil ($M.T^{-2}$)

Θ=effective/normalized water content (-)

θ = Volumetric water content ($L^3.L^{-3}$ or %)

θ_s = saturated volumetric water content ($L^3.L^{-3}$)

θ_r = residual volumetric water content ($L^3.L^{-3}$)

λ = pore size distribution index in equation of Brooks and Corey (-)

ρ_b = Soil bulk density ($M.L^{-3}$)

ρ_{d} = Soil particle density ($M.L^{-3}$)

ρ_w = density of water ($M.L^{-3}$)

Φ = Potential ($M.L^{-1}.T^{-2}$)

Ψ = potential head (L)

ψ_e = air entry suction (L)

ψ_{en} = envelope or overburden head (L)

ψ_m =matric head (L)

ψ_o = osmotic head (L)

ψ_p = pressure head (L)

ψ_t = total water head (L)

ψ_z = head due to height or position or geodetic head (L)

ω = gravimetric water content ($M.M^{-2}$ or %)

9.2 Abbreviations

BC = Brooks and Corey equation

B (1, 2… 9) = Big Core samples from one to nine

BMA = Mean for All Big core samples

BMV = Valid Mean for Big core samples

CaS = Capacitive sensors

CoS = conductivity sensors

FC = Field Capacity

FX = Fredlund and Xing equation

IAEA = International Atomic Energy Agency

NM = Not measured

NMM = Neutron moisture meter
PSD = Particle Size Distribution
PTF = Pedotransfer Function
PWP = Permanent Wilting Point
RETC = Retention Curve software computer program for fitting measured data to different models developed for soil water retention curve
S (1, 2…9) = Small Core samples from one to nine
SMA = Mean for All Small core samples
SMV = Valid Mean for Small core samples
SSQ = Sum of Square (residual)
SWRC= Soil Water Retention Curve
TDR= Time Domain Reflectometer
TS= Thermal Sensors
VG= van Genuchten equation

10. Appendices

Appendix A

Values of Some Numbers (Constants)

$e = 2.7182818$

$g = 9.81 m.s^{-2}$

$\rho_w = 1000 kg.m^{-3}$ (at 20 ^{0}C)

$\gamma = 0.0728$ N/m (at 20 °C)

$\pi = 3.1415927$

1 bar = 1019.71621298cm

1 bar = 100KPa

Appendix B

Physical Properties of Silica Sand (ST 56) according to Sklopísek Střeleč, a.s.

No	PHYSICAL CHARACTERISTICS	
1	Melting point (°C)	1,780
2	Particle Density (g/cm^3)	2.65
3	Hardness, Mohs	7
4	Loss by annealing (%)	0.23
3	Sintering °C	1 560
6	Humidity in a wet state (%)	8.0 max.
7	Humidity in a dry state (%)	0.2 max.
8	Bulk Density (g/cm^3)	1.5
9	Total Porosity (%)	37.3
10	Percolation (mm/h)	143
11	Critical Tension (mm)	657

Taken from Sklopisek Střeleč website (see References)

N.B.The figure is based on average values

Appendix C

Particle size distribution of Silica Sand ST 56 according to Sklopísek Střeleč, a.s.

Microns	% Passing	% Retained
1400	100	0
1000	100	0
710	99.9	1
500	97.9	1.1
355	95.9	2
250	89.9	6
180	75.8	14.1
125	33	42.8
90	11.3	21.7
63	2.2	9.1
pan	0	2.2

Taken from website: http://www.glassand.eu/GB/index.php?page=katalog#

Appendix D

Procedure of sample preparation

Appendix E

Samples during the retention curve measurement

(a) Sample in sand tank (b) Sample in Pressure

Plate

(c) Sample to be oven--dried (d) Weighing sample

Appendix F

Some indirect soil water content measuring methods

Method	Surrogate measurement	Explanation
NMM	Count of slow neutrons around a source of fast neutrons	A radioactive source emits fast neutrons (5 MeV), which lose energy as they collide with other atoms, in particular hydrogen. The surrogate is the concentration of slow neutrons. Since the only rapidly changing source of hydrogen in the soil is water, θ can be calibrated vs. the count of slow neutrons.
TS	Heat conductivity or heat capacity of the soil	A pulse of heat is generated and the subsequent rise or fall in temperature of adjacent soil is measured over time. Soils are a poor conductor of heat, and water a good one, so the amount of heat or rate of heat transmission is closely related to θ.
TDR	Travel time of an electromagnetic pulse	A fast rise time electromagnetic pulse is injected into a waveguide inserted into or buried in the soil. The time required for the pulse to travel along the metal rods of the waveguide is determined by the bulk electrical permittivity of the soil. The θv is a major factor influencing the bulk permittivity (BEC). True TDR involves capture of a waveform and analysis to find the travel time of the highest frequency part of the pulse.
CaS	Frequency of an oscillating circuit	An oscillating current is induced in a circuit, part of which is a capacitor that is arranged so that the soil becomes part of the dielectric medium affected by the electromagnetic field between the capacitor's electrodes. The θ influences the electrical permittivity of the soil, which in turn affects the capacitance, causing the frequency of oscillation to shift.
CoS	Electrical conductivity of a porous medium in contact with the soil	An alternating current voltage is placed on two electrodes in a porous material in contact with the soil, and the amount of current is a measure of the conductivity and amount of water in the porous material between the electrodes. These are used for estimation of soil water tension (suction), not θ.
Tensio-meters	Matric and gravitational soil water potential components	Capillary forces retaining water in the soil pores are connected through the soil water to water in a porous cup connected to a tube filled with water. This generates a negative pressure within the tube, which can be measured with a vacuum gauge. These are used for estimation of soil water tension (suction), not θ.

From IAEA, Hignett and Evett (2008), p. 9

Where: NMM is Neutron moisture meter; TS is Thermal sensors; TDR is Time Domain Reflectometry; CaS is capacitive sensors and CoS is conductivity sensors like granular matrix sensors & gypsum blocks)

Appendix G

Summary of direct and indirect methods of soil suction measurement

Technique			Φ range (KPa)	Equil. time	Principle(s)	Limitation(s)
Direct method	Matric suction	Axis-translation Technique	0-1500	hours	Artificially increasing the atmospheric pressure experienced by a soil sample while maintaining the pore-water pressure to a positive reference pressure to avoid measuring negative pore-water pressure in changing matric suction. (Pan et al., 2010)	-limited to lower suction -long equilibrium time -doesn't yield instantaneous results when used to impose matric suction
		Tensiometer	0-85	hours	Measurement of vacuum created in the tensiometer tube due to absorption of water by the dry soil from porous cup (Shukla and Lal, 2004).	-Low Range -Long response time -Air entry due to poor contact
		Suction Probe	0-1500	Minutes	based on the equilibrium between the pore-water pressure in the soil and the pore-water pressure in the water compartment (Pan et al., 2010)	- there may be cavitation and air diffusion through the ceramic head -limited by air entry value of the ceramic cup
Indirect method of soil suction measurement		In-contact filter paper technique	$1\text{-}10^5$(all)	7-14 days	Evaluating changes in matric potential with change in water content of a porous material (Shukla and Lal, 2004).	-Hysteresis of the material -Calibration of all material
	Osmotic	squeezing technique	0-1500	days	Squeezing a soil specimen to extract the macro pore water and then measuring its electrical conductivity (Peroni and Tarantino, 2005)	-Osmotic pressure has prominent effect on higher stage of SWRC while the method measure the lower one from larger pores
	Total suction	Psychrometer technique	80-1500	1 hour	Monitoring relative humidity of vapor in equilibrium with the liquid phase in soil (Shukla and Lal, 2004)	-Extremely sensitive to temperature
		chilled-mirror hygrometer	$150\text{-}3*10^4$	10 min.	Based on equilibrating the liquid phase of the water in a soil sample with the vapour phase of the water in the air space above the sample in a sealed chamber under isothermal condition (Pan et al., 2010)	-affected by contaminated soil -not good for non-isothermal condition

Appendix H

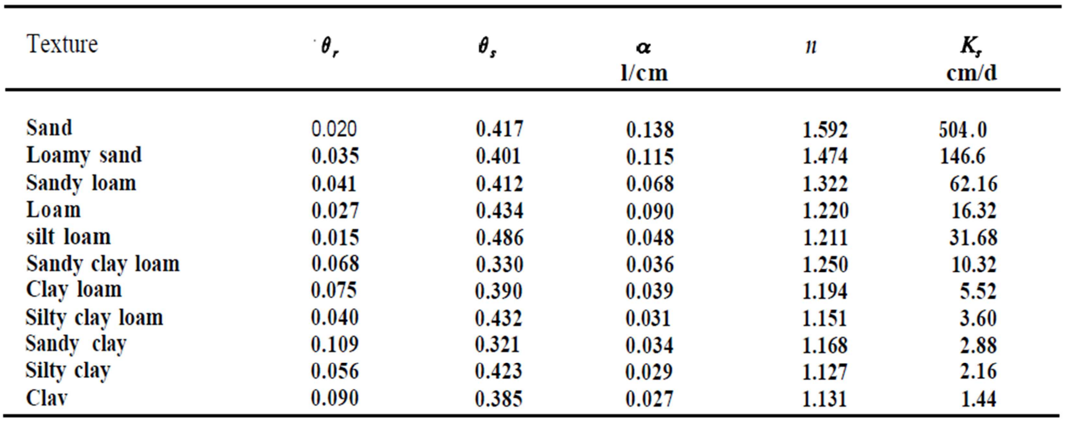
Summary of some equations for soil water retention curve modeling/fitting

Equation	Reference	Description
$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+q(\psi)^n\right]}$	Gardner (1958)	- q is curve fitting parameter related to air entry value & n is a curve fitting parameter related to inflection point of SWRC -Equation first proposed for permeability function & emulates SWRC
$\theta = \theta_r + (\theta_s - \theta_r)\left(\frac{\psi_e}{\psi}\right)^{\lambda}$	BC (1964)	Where: λ is the pore size distribution index
$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha * \psi)^n\right]^m}$	VG (1980)	Where: α, n & m are empirical constants affecting the shape of SWRC
$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]^m\right\}}$	FX (1994)	Where: a, n & m are empirical constants that affect the shape of the retention are curve - To estimate residual water content -With *five parameters*: a, n, m, Θ_s & Θ_r
$\theta = C(\psi)\ \frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]^m\right\}}$ Where: C(ψ)= $\frac{-\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{10^6}{\psi_r}\right)}+1$	FX (1994)	-Where: a, n & m are empirical constants that affect the shape of the retention are curve -C(ψ) is correction factor -To estimate the whole range of interest [0, 10^6] cm of suction. -With *four parameters*: a, n, m and Θ_s

BC = Brooks and Corey, VG = van Genuchten, FX = Fredlund and Xing

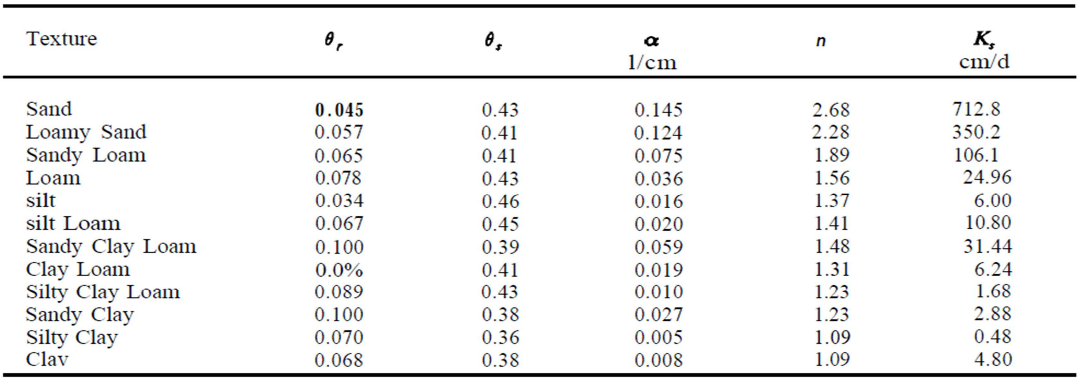
Appendix I

Average values for selected water retention and hydraulic conductivity parameters for major textural groups:



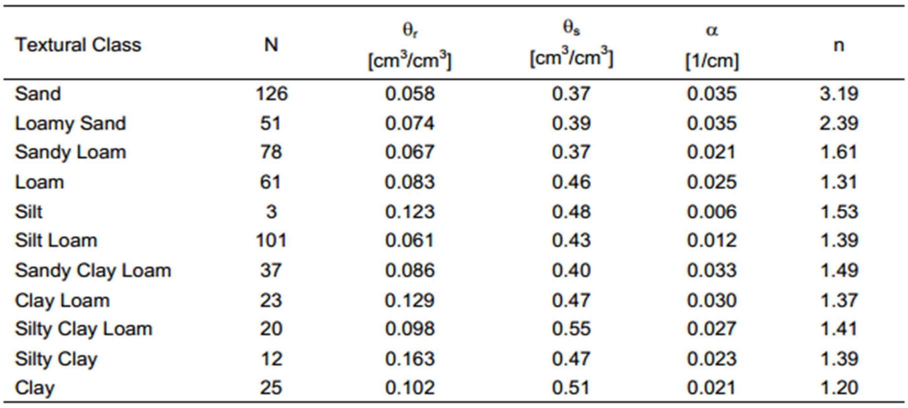
Texture	θ_r	θ_s	α 1/cm	n	K_s cm/d
Sand	0.020	0.417	0.138	1.592	504.0
Loamy sand	0.035	0.401	0.115	1.474	146.6
Sandy loam	0.041	0.412	0.068	1.322	62.16
Loam	0.027	0.434	0.090	1.220	16.32
silt loam	0.015	0.486	0.048	1.211	31.68
Sandy clay loam	0.068	0.330	0.036	1.250	10.32
Clay loam	0.075	0.390	0.039	1.194	5.52
Silty clay loam	0.040	0.432	0.031	1.151	3.60
Sandy clay	0.109	0.321	0.034	1.168	2.88
Silty clay	0.056	0.423	0.029	1.127	2.16
Clay	0.090	0.385	0.027	1.131	1.44

(a) According to Rawls et al. (1982) and cited by van Genuchten et al. (1991), pp.40



Texture	θ_r	θ_s	α 1/cm	n	K_s cm/d
Sand	0.045	0.43	0.145	2.68	712.8
Loamy Sand	0.057	0.41	0.124	2.28	350.2
Sandy Loam	0.065	0.41	0.075	1.89	106.1
Loam	0.078	0.43	0.036	1.56	24.96
silt	0.034	0.46	0.016	1.37	6.00
silt Loam	0.067	0.45	0.020	1.41	10.80
Sandy Clay Loam	0.100	0.39	0.059	1.48	31.44
Clay Loam	0.0%	0.41	0.019	1.31	6.24
Silty Clay Loam	0.089	0.43	0.010	1.23	1.68
Sandy Clay	0.100	0.38	0.027	1.23	2.88
Silty Clay	0.070	0.36	0.005	1.09	0.48
Clay	0.068	0.38	0.008	1.09	4.80

(b) According to Carsel and Parrish (1988) and cited by van Genuchten et al. (1991), pp.41



Textural Class	N	θ_r [cm^3/cm^3]	θ_s [cm^3/cm^3]	α [1/cm]	n
Sand	126	0.058	0.37	0.035	3.19
Loamy Sand	51	0.074	0.39	0.035	2.39
Sandy Loam	78	0.067	0.37	0.021	1.61
Loam	61	0.083	0.46	0.025	1.31
Silt	3	0.123	0.48	0.006	1.53
Silt Loam	101	0.061	0.43	0.012	1.39
Sandy Clay Loam	37	0.086	0.40	0.033	1.49
Clay Loam	23	0.129	0.47	0.030	1.37
Silty Clay Loam	20	0.098	0.55	0.027	1.41
Silty Clay	12	0.163	0.47	0.023	1.39
Clay	25	0.102	0.51	0.021	1.20

(c) According to Leij et al. (1996) and cited by Tuller and Or (2003), pp.9

*N indicates the number of soils or samples from which average values were calculated

Appendix J

Paired (small and big core) samples t-test for volumetric water content ($cm^3.cm^{-3}$) at different applied pressure using excel sheet

pF	0		1.34		1.6		1.74		1.85		3.37	
Ring size	**Small**	**Big**	Small	Big	Small	Big	Small	Big	Small	Big	Small	Big
θ ($cm^3.cm^{-3}$)	0.3912	0.4014	0.3564	0.3340	0.3500	0.3286	0.3423	0.3172	0.3369	0.3118	0.0077	0.0128
	0.3976	0.3924	0.3563	0.3194	0.3489	0.3152	0.3384	0.3056	0.3336	0.2996	0.0086	0.0097
	0.3980	0.3970	0.3449	0.3309	0.3405	0.3266	0.3316	0.3178	0.3262	0.3140	0.0149	0.0104
	0.3963	0.3965	0.3576	0.3386	0.3500	0.3339	0.3402	0.3220	0.3349	0.3188	0.0079	0.0106
	0.3978	0.3976	0.3412	0.3464	0.3316	0.3405	0.3245	0.3318	0.3191	0.3261		
	0.3982	0.4025	0.3388	0.3638	0.3351	0.3594	0.3271	0.3500	0.3172	0.3462		
t-value	**0.47**		**0.18**		**0.25**		**0.19**		**0.28**		**0.58**	

*All calculated t-values are less than critical t-values (from two tailed t-table is **2.57** with 5 df and **3.18** with 3 df for 95% confidence interval or α=0.05)