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Diploma thesis

Laboratory determination of soil water retention curve of biochar treated soils

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Declaration

I declare that my thesis "Laboratory determination of soil water retention curve of biochar treated soils" was written solely by myself, and was not forged. I worked separately under supervisor of the thesis and was using literature and other information sources as cited in the work and listed in the references at the end of the work.

In Prague on April 13, 2017

Signature: _______________

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SUMMARY

Recently, potential of biochar amendment into soil has gained a considerable interest globally. Biochar is a carbon rich material produced mainly by slow pyrolysis. Biochar treatment is supposed to reduce bulk density, improve soil structure, and soil hydrophysical properties. Improvement of plant water availability is one of the main reasons why biochar is applied into the soils while biochar amended soils could also reduce the amount of irrigation water required by crops, or help to the crops to overcome drought periods in rainfed agriculture. Therefore, adding biochar into soil can positively affect crop yield. Main objective of the thesis was to determine and evaluate soil water retention curve for selected soils from the Czech Republic mixed with different amount of biochar in laboratory, and the biochar itself.

The study was conducted on repacked soil core samples with specific attention to maintaining the dry bulk density of the soils in order to reduce the natural soil heterogeneity and thus allow a comparison of the effects of various biochar admixtures on the selected soils. Three soils were chosen: first, graded fine silica sand; second, silty loam chernozem soil which was collected in Prague-Suchdol; and third, clay loam luvisol from Prague-Uhříněves. Three concentrations of biochar were used: control treatment without any biochar addition and two treatments with biochar admixture, 0.001 $g.g^{-1}$ and 0.01 $g.g^{-1}$, which correspond roughly with field application rates 2.6 or 26 $t.ha^{-1}$, respectively. Each treatment was done at least three-times. Evaporation method using Hyprop device (UMS GmbH.) was employed to measure the soil water retention curve. All data were processed and statistically evaluated.

Results showed small increase of water retention in case of the higher biochar concentration, in average 3.5% by volume on luvisol, while effect on sand was not statistically significant (P=0.05), yet noticeable, and effect on chernozem was not noticeable. Objectives of the thesis were fulfilled and results provided important information for practical use and future studies.

Keywords: biochar, carbonisation, soil water retention curve, soil water potential measurement, plant available water

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1. INTRODUCTION

Soils are crucial to life on Earth. Quality of the soil determines nature of the plant ecosystems and capacity of the land to support animal life and society. Obviously, the degree to which we are dependent on soils is likely to increase in the future. Soil will continue to supply us with nearly all of our food in addition to most of the fiber we use for paper and clothing.

The organic proportion of soil is a complex of substances and there are many terms which can describe these components. Most of all textbooks use the term soil organic matter which describes all organic components of a soil – living biomass, dead roots and other residues and amorphous and colloidal mixture of complex of organic substances. Carbon (C) plays main role in the chemical structure of all organic substances which is essential for plant growth (Brady and Weil, 2008). Biochar is a carbon-rich material produced by the slow pyrolysis of biomass and is suggested to be added to agricultural soils to improve soil functioning. Biochar can enhance plant growth by increasing soil water-holding capacity, nutrient retention due to an increase in the cation exchange capacity or by improving physical characteristics of the soil and mycorrhizal competences (Hagner et al., 2016). It is likely that changes in microbial activity, community structure and functional diversity could impact the crop productivity. Comparing biochar to that of fresh crop residues estimated C-residence time of biochar in soils is in the range of hundreds to thousands of years, while crop residue is in range of decades. Increased crop yield is commonly reported as a benefit of adding biochar to soils. (Jeffery et al., 2011).

There are many types of biochar produced from pyrolysis. Pyrolysis of wood-based feedstock generate coarser and more resistant biochar because of xylemic structure of the parent material, while biochar produced from crop residues and manures are finer and nutrient rich, thus more readily degradable by microbial communities (Verheijen et al., 2010).

Biochar application to soils is currently being considered as a manner how to mitigate climate change by sequestering C while simultaneously improving soil properties and functioning (Jeffery et al., 2011). Due to population growth, there is higher demand for agricultural products. Since the 1940s, farmers have begun to purchase imported manure and manure which is not locally produced and causes more greenhouse gas emissions as well as underground water pollution. Therefore, biochar may be one way of avoiding further air and water pollution (Barrow, 2012).

2. HYPOTHESIS AND OBJECTIVES OF THESIS

Hypothesis:

Application of biochar increases soil porosity and thus affects soil hydraulic properties by several mechanisms; i.e. direct contribution caused by intrinsic biochar porosity, and interaction with the soil matrix and improvement of the soil structure. Thus application of biochar enhances soil water retention. It is assumed that the higher the application rate, the higher the effect is.

Objectives:

The main objective is to determine and evaluate soil water retention curve of three different soils which are mixed with different amount of biochar in laboratory in sufficient number of replicates. The study will be conducted on repacked soil core samples with extra attention to dry bulk density of the soils. Maintaining constant dry bulk density (and thus soil porosity) reduces natural soil heterogeneity and thus allows a comparison of the effects of various biochar admixtures in the selected soils. An assessment of hydrophysical properties of the used biochar is a secondary objective.

3. LITERATURE REVIEW

3.1. Biochar

Biochar is a carbon-rich material produced mainly by the slow pyrolysis of biomass, it is suggested to be added to agricultural soils to improve their functions. Biochar may enhance plant growth, for example by increasing soil water-holding capacity (WHC) and nutrient retention due to an increase in the cation exchange capacity (CEC) or by improving physical characteristics of the soil and mycorrhizal competences (Hagner et al., 2016). Biochar reduces soil acidity and decreases liming needs. In most agricultural soils pH is low and needs to be increased. Biochar retains nutrients in soil directly through the negative charge that develops on biochar's surface, and this negative charge can buffer acidity in the soil. CEC is one of many factors involved in soil fertility. Cations in plant nutrients are mainly calcium (Ca^{2+}), potassium (K^{+}), magnesium (Mg^{2+}) and others. Plants can uptake nutrients in these simple forms through their roots. Organic matter such as biochar can hold these positively charged nutrients because they have negatively charged sides. If the soil has a low CEC, it is not able to retain such nutrients properly, and nutrients are often washed out with water (Major, 2010).

Since 1940s, agriculture has shifted from using locally produced manure and compost to purchased, often imported chemical fertilizers. With oil and phosphate suppliers dwindling, fertilizers were becoming costly and unsafe, resulting in lead-dependency, causing soil pollution and providing little maintenance of organic carbon in soil. Alternatives are manure and compost but for many farmers these are difficult to get and if usage can cause serious groundwater and stream nutrient pollution. Biochar could be a way of disposing of agricultural wastes, human sewage, livestock manure etc. with less greenhouse gas emissions (Barrow, 2012). When these bio solids are thermally treated via pyrolysis, they reduce waste volume and therefore transport costs of manure Biochar further reduces pathogens and heavy metal bioavailability in soils because their presence in the carbonaceous matrix is relatively resistant to natural leaching. (Inguanzo et al., 2002).

Soil nutrient depletion, decreasing agricultural productivity and anthropogenic climate change threaten sustainability of agricultural production. In recent years, application of biochar to soil has emerged as a strategy for sequestering carbon, reducing greenhouse gas emissions and improving soil quality (Agegnehu et al., 2016).

Some researchers define general term to describe all carbon rich residues from fire or heat, e.g. charcoal, coal; this name is black carbon (BC). BC, a soot component, is a potent climate driver that absorbs sunlight in the atmosphere and can speed up melting when it falls on snow and ice. Soot is a mix of amorphous microscopic particles that contains BC, organic, and smaller amounts of sulfur and other chemicals. Soot from combustion usually appears black because it contains a high fraction of BC, which absorbs all colors of the light spectrum (Bachmann, 2009). BC acts as a sorbent of organic compounds. It can have sorption efficiency of 1 to 3 orders of magnitude larger than soil organic matter. When BC is added into soils, it may become an ecosystem C source or sink. From the context BC is produced by heating biomass in a low or zero oxygen environment (Durenkamp et al., 2010; Zimmerman et al., 2011).

Such high amount of carbon can be rather uncooperative to decomposition, so it may stably separate carbon (Koide et al., 2011). The estimated carbon residence time of biochar in soil is in the range of hundreds to thousands of years, while crop residue is in the range of decades (Jeffery et al., 2011). Biochar is not a single material, and its characteristics vary depending upon what it is made from and how it is made. Most biochars have a small easily decomposable fraction and much larger stable fraction, which is estimated to range from several hundreds to a few thousand years (Major, 2010).

Some scientists support a theory, that there exists a large imbalance between carbon released to the atmosphere and carbon uptake by other compartments that lead to a continued increase in atmospheric carbon dioxide. Thus, it should be important to focus on new methods development to hold carbon in the stable form that can be stored outside of the atmosphere for longer time periods (Awasthi et al., 2016). This storage outside of atmosphere is called carbon sequestration. By this process CO_2 is removed from the atmosphere and stored in the ocean, terrestrial environments, such as vegetation, soils, and sediments (Sundquist et al., 2008).

The major deficiency associated with sewage sludge composting are nitrogen loss and greenhouse gas emissions during the decomposition of organic waste and high levels of heavy metals and salts in the end products. Biochar attracted a lot of researchers with focus on the application of this material into soils, because biochar contributes to carbon storage but at the same time acts as fertilizers (Steinbeiss et al., 2009). Biochar application rates depend on soil type and crops. In the published studies was reported that the positive effect of biochar application on crop could be seen with rates of 5- 50 $t.ha^{-1}$ with appropriate nutrient management. This is a large range, but often when several rates are used, the plots with higher application of biochar show better results (Major, 2010).

Biochar can be applied to soils mechanically, by hand, and with assistance of animals. Table 1 summarizes various methods that may be used for biochar application to the agricultural soils (Kgope et al., 2015).

Table 1. Summary of different biochar application techniques (Kgope et al., 2015).

Application method	Description	Potential impacts / benefits
Trench and fill	- Cutting trenches and using some device to fill the trenches with biochar	- It is unknown how biochar migrates vertically through the soil profile → its influence may be worsen at small distances from the point of application
Top dressing	- Adding biochar to the soil surface can be done by hand on a small scale or on larger scale by using spreaders or similar device	- Hand application use in large scale is not possible due to labor intensity - Top-dressed biochar is prone to wind and water erosion - Tonnages of biochar application may be very low per hectare - In case of larger scale usage, additional equipment is necessary, which increase cots and the carbon footprint
Spreading and disking	- This technique is used in conventional agricultural application - Disking pass is used to enable shallow incorporation of the biochar into the soil	- Technology offers precise dosing - Wind and water erosion has to be kept on mind during the biochar application
Deep banding	- Application of amendment in a narrow band without disturbing the entire soil surface. It allows biochar to be placed inside the soil, while minimizing soil disturbance and it is possible to apply biochar after crop establishment	- Low-impact application methods - The biochar is deposited directly in the rhizosphere - All process is relatively labor intensive - Relatively low rates of application are technically possible with one pass

Mixing biochar with other soil amendments, for instance manure, compost or lime before application can reduce number of field operations, and thus can increase efficiency of soil fertilizing (Kgope et al., 2015).

Due to resistance to decomposition in soil, single application can have beneficial effect over several growing seasons in the field. Thus, biochar does not have to be applied each year as is usually in case of manures, compost, and synthetic fertilizers. Nevertheless, biochar itself cannot be considered as source of nutrients (due to high ash content); it is recommended to mix it with other materials such as synthetic fertilizers, manure or compost in order to enhance its value as a soil amendment. Moreover, biochar has been shown to retain nutrients against leaching (Novak et al., 2009). Applying biochar to soil for improving its fertility, biochar should be ideally located near the soil surface in the root zone, where the nutrient cycling and uptake by plants take place (Major, 2010).

Some researchers pointed out the fact that biochar added into the initial stage of the composting process can include changes in the microbial community (Wei et al., 2014). The addition of biochar could increase the temperature during thermophilic phase, which can contribute to faster decomposition of organic matter due to microbial activity which means added biochar provides a better habitat for microorganisms (Czekala et al., 2016). The soil biota is vital to functioning of soils and provides many essential ecosystem services. Understanding the interactions between biochar, used as a soil amendment and the soil biota is vital (Verheijen et al., 2010). Besides the fact, that biochar treatments reduce bulk density, improve aeration, and textural properties of soil (by changing soil structure), it also increases water retention (Ajayi et al., 2016). Biochar application leads to an increased water retention of soils and it seems that this will have a positive effect on soil activity, and the ecosystem services which it provides. Soil is often an aquatic habitat, as micropores in contain full of water, apart from very extreme drought. This is vital for survival of many microbial species which require presence of water for their mobility and function (Verheijen et al., 2010).

Improvement of water availability is one of the reasons why biochar is applied into agricultural soils. From this point of view, biochar has similar properties to soil organic matter (SOM). SOM has a positive effect to crop moisture availability in agriculture and therefore biochar may also positively affect water availability for plants (Zwart and Hummelink, 2014). Biochar amended soils could reduce the amount of irrigation water required by crops. Limiting the amount of water needed for given crop is advantageous in agriculture of arid and semi-arid regions of the world where drinking water and water as such, is scarce. Thus, biochar plays a significant role in water management aiming to reduce agricultural input and maximize crop yield (Libutti et al., 2013).

Adding biochar to soil can improve crop yield, especially in soils with poor fertility. The effect of biochar from cow manure on maize yield, increased nutrient uptake and improved physicochemical properties of a dryland sandy soil, was studied by Tang et al. (2013). Results showed that maize yield and nutrient uptake were significantly improved with increased biochar application rate. The observed effects on soil fertility have been explained mainly by a pH increase in acid soils or improved nutrient retention through cation adsorption. Biochar has also been shown to change soil biological community composition and abundance. Such changes may have effects on nutrient cycles or soil structure and thus, indirectly affect a plant growth (Lehmann et al., 2011).

Phosphorus is an essential element for plant growth and its deficiency in soil restricts crop yield. Many agricultural lands in the world are suffering from phosphorus deficiency. Numerous researches have shown that biochar can have reservoir function of phosphorus for soils and that a fraction of this phosphorus in a form which is available for plant (Zhang et al., 2016). The main role of biochar in the soil is to increase retention of nutrients. Thus, the microscopic surface area in one of the crucial properties of biochar, which determines the capability of nutrients and water adsorption. There is a wide variation between biochar samples. In the Figure 1 are given examples of biomass for biochar production and in the Figure 2 are shown their microscopic surfaces after pyrolysis at 500 °C. Biochar from wood stem, sugarcane bagasse and Palm kernel shell, develops large microscopic surface area over 190 $m^2.g^{-1}$ and in contrast the surface area of coco peat and wood bark is less than 15 $m^2.g^{-1}$. (Lee et al., 2015).

3.1.1. European biochar certificate

There is a European biochar certificate (EBC), and in order to acquire it, the main criteria must be met. EBC has been developed by biochar scientists and it ensures a sustainable biochar production and low hazard use in agronomic systems. Feedstocks used for production of biochar cannot be transported over distances greater than 80 km. All non-organic contaminants, waste such as plastic, rubber and electronic scrap must be removed. Biochar C content must be higher than 50 % of the dry matter. Details on bulk density and water content are necessary for the production of homogenous substrate mixtures. There are two biochar quality grades – basic and premium according to the Germany’s Federal Soil Protection Act and the Switzerland’s Chemical Risk Reduction Act, respectively. The premium one has higher criterions of heavy metals. Threshold which has to be kept in biochar´s total dry mass for the basic quality grade are given in Table 2. Biochar may be produced from wood from forests of short rotation forestry plantation, or other biomass for biochar production see Table 3 (EBC, 2016).

Figure 1. Examples of different types of biomass used for biochar production (Lee et al., 2015).

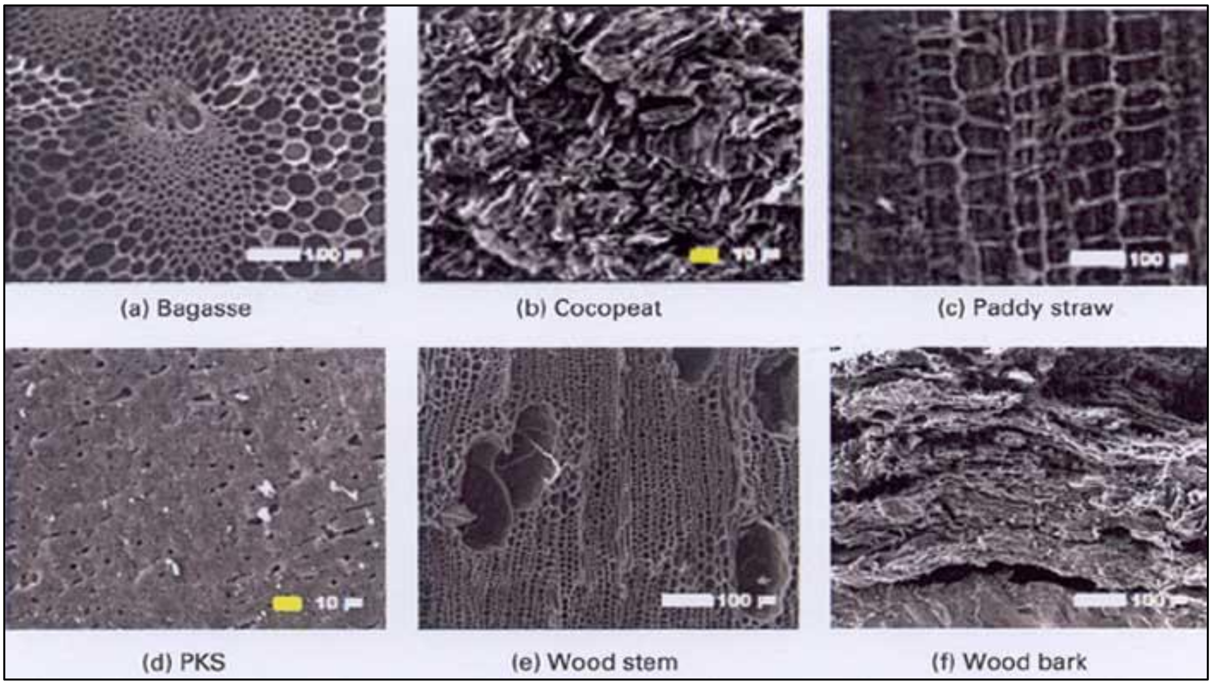


Figure 2. Microscopic structure of biochars made of different types of biomass at 500 °C (Lee et al., 2015).

Table 2. Thresholds for the biochar's basic quality grade (EBC, 2016).

Element	**Threshold ($g.t^{-1}$)**	**Element**	**Threshold ($g.t^{-1}$)**	**Element**	**Threshold ($g.t^{-1}$)**
Pb	< 150	**Ni**	< 50	**Cr**	< 90
Cd	< 1.5	**Hg**	< 1	**As**	< 13
Cu	< 100	**Zn**	< 400		

Table 3. Biomass for biochar production (EBC, 2016).

Origin	**Source of biomass**	**Special requirements for basic quality of biochar**
Local sorted waste collection	Biodegradable waste, kitchen waste and food scraps	
Garden waste	Plants, roots	Soil as an additive and cannot be more than 10 % in DM
	Leaves	Waste from the street cleaning is not included
	Branches from trees and bushes	
	Biomass from landscape maintenance – hay, grass	Only waste which cannot be further used as a feed
Agriculture and forestry	Grain, feed, residues from plants used as renewable energy	
	Bark, wood chips, sawdust, shavings and wood wool	Only untreated wood
	Residues from harvest – straw, husks, grain, fruits	Only waste that can no longer be used as food for human or animal food
Vegetable production	Material from washing, peeling, centrifuging and other separation – fiber, peels, pulp	
Maintenance of water surfaces	Alluvial biomass, residues from fishing, material from banks and water plants	

3.2. Pyrolysis

Biochar is one of the byproducts of pyrolysis and may be useful as a soil amendment due to its unusual chemical and physical characteristics. This byproduct can be described as a black, fine grained, extremely porous, lightweight and stable form of carbon that is very similar to charcoal (Méndez, 2013).

Pyrolysis is the process by which carbon based matter is taken into a high temperature in an oxygen-devoid environment and the result is a breakdown of the matter into its constituent chemical elements (Saidak, 2011). This thermochemical conversion is one way of liquid fuel production which are condensed as heavier gases, called bio-oil, and lighter gases, like hydrogen and methane called syngas. Pyrolysis is the first step that defines thermochemical conversion and characterizes the product yield into condensable tars, non-condensable gas (which are known in commercial production as synthetic gas or syngas), and the last by-product from pyrolysis is biochar (Boateng et al., 2006). Scheme of pyrolysis according to Aston University (2014) is shown in Figure 3.

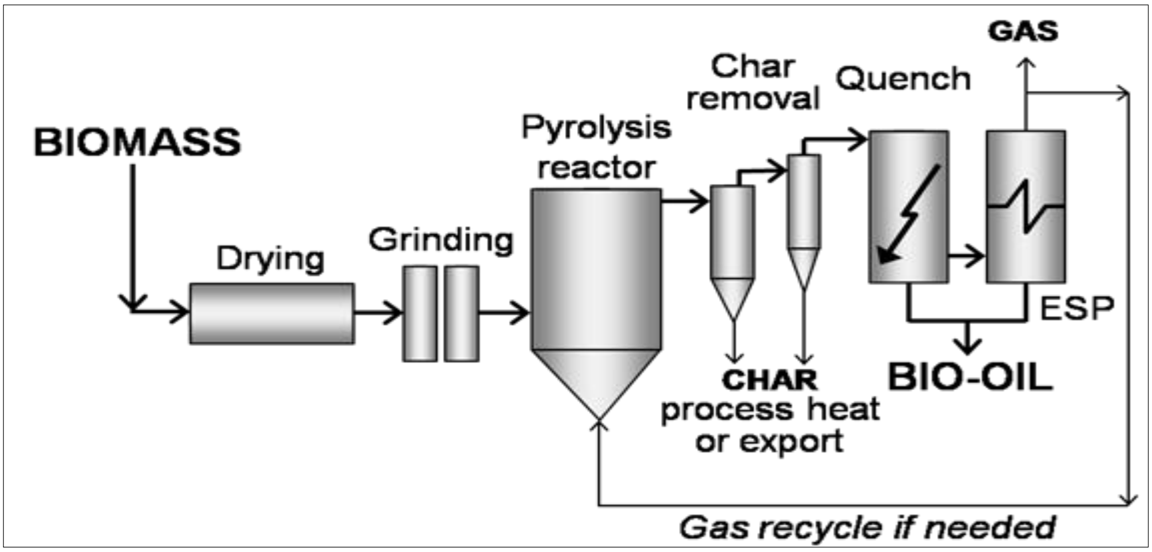


Figure 3. Scheme of pyrolysis (Aston University, 2014).

There are three types of pyrolysis – fast, intermediate and slow. Three products – gas, liquid and solid matter are always produced but the proportion can vary. When biomass is used as material for slow and fast pyrolysis processes, it is possible to get biochar and bioenergy. This bioenergy can be used as an alternative to fossil energy. However, bioenergy production depends on pyrolysis conditions, where slow pyrolysis means a lower yield of liquid fuel and more biochar, while fast pyrolysis is vice versa (Ahmad et al., 2014), see in Table 4.

Table 4. Product yield of each type of pyrolysis (Aston University, 2014).

Method	**Liquid**	**Biochar**	**Gas**
Fast	75 %	12 %	13 %
Intermediate	50 % in 2 phases	25 %	25 %
Slow	35 %	35 %	30 %

Recently there has been an increasing interest in low temperature pyrolysis - between 300 °C and 1000 °C for organic materials to produce biochar (Smith et al. 2010; Jeffery et al., 2011; Méndez et al., 2013). Fast pyrolysis has been optimized for bio-oil production and typically 12-20 % of the feedstock mass is converted into solid-state biochar (Kim et al., 2012).

This diploma thesis is focused mainly on biochar, which is most commonly gained from slow pyrolysis. Slow pyrolysis is done at low temperatures and low heating rates. The practice of pyrolysis was used thousands of year ago in the Amazon rainforests in order to create biochar which was used to enrich and stabilize the nutrients poor rainforest soils (Saidak, 2011).

During this kind of pyrolysis, vapor residence time is too high (from 5 to 30 min). Vapor residence time is defined as the average amount of time vapor (primary pyrolysis vapor) spent in the heated zone before being rapidly cooled (Luque et al., 2016). Components in the vapor phase continue to react with each other which results in formation of solid char and other liquids. There is an extra energy input demand because of long residence time and low heat transfer (Jahirul et al., 2012).

3.3. Soil physical and hydrophysical properties

When studying the influence of biochar on soil hydraulic and other properties, firstly, these soil properties and their interactions must be described and understood.

- Brady and Weil (2008) indicate there are many key roles which soil plays:
- Supports growth of higher plants, because soil represents a medium for plant roots and supplying nutrient elements that are essential for the entire plant. The properties of soil often determine quality of present plants.
- Soil properties are the principal factor controlling the fate of water in the hydrologic system.
- Works as nature's recycling system.
- Provides habitats for many living organisms.
- Influences composition and physical condition of the atmosphere by taking up and releasing carbon dioxide, methane and other gases.

3.3.1. Soil water content

Many soil properties depend on water content; mechanical properties, which depend on water content, are plasticity, consistency, compactibility, permeability, strength, and also in solid-state with higher content of clay shrinking and swelling, change of bulk density porosity and pore size distribution. Water in soil competes with air and content of water or air depends on respiration of the roots, activity of microorganisms and the chemical state of the soil (Hillel, 2004). Soil water content changes constantly. Water in soil occupies pore spaces and competes with soil gas phase. Highly substantial volume of water is stored in soils (Or and Wraith, 2002).

According Or and Wraith (2002). Soil water content can be expressed by:

a) Volume of water per bulk volume of soil, Equation 1:

$$\theta_v = \frac{V_w}{V_s} \tag{1}$$

Where:

V_w……………………volume of water (cm^3)

V_s……………………..volume of the soil (cm^3)

b) Mass of water per mass of oven dry soil. Expressed by following Equation 2:

$$w_m = \frac{m_w}{m_s} \tag{2}$$

Where:

m_w……………………mass of water (g)

m_s……………………..mass of the soil (g)

Soil water content either by volume or by mass is determined by a standard gravimetric method, which consists of weighing the moist soil sample followed by weighing the dry soil sample which had been dried to the constant mass in an oven (at 105°C for most soils). Volume of the soil sample is most widely obtained as a volume of a core sampling ring (Kutílek, 1978).

3.3.2. Dry bulk density

Bulk density (BD) is one of the most important soil characteristics affecting rainfall infiltration (Basso et al., 2012). BD is the weight of dry soil divided by the total soil volume, see Equation 3. Total soil volume is a combination of volume of solid fraction and pores which can be filled by water, air or both. The soil bulk density and porosity reflects the size, shape and arrangement of particles and the soil structure. BD together with porosity indicates the sustainability of plant roots growth, soil permeability and vitality. It is suitable to have soil with a low bulk density (below 1.5 g.cm^{-3}), because of optimal movement of air and water through the soil (Brown and Wherrett, 2016).

$$\rho_d = \frac{m_s}{V_s} \quad (3)$$

Where:

m_s ………..mass of the soil (g)

V_s ………..volume of the soil (Kopecky´s sampling ring has volume 250 cm^3)

3.3.3. Soil water potential

It is possible to describe the state of water in soil by two parameters: one is soil water content, or in other words, the amount of water per unit of soil. The second parameter is total soil water potential, or the energy state of water in the soil. Both parameters are used for different findings. Water content is useful when water balance in the soil needs to be described, which means how much water is moving in / out, or being stored. Nevertheless, total soil water potential is often preferred to water content because it determines how water moves in a soil; from the soil to the plant. Moreover, by water potential, it is possible to determine availability of water for plants, design irrigation, or determine the mechanical stress state of soil. Potential energy of water is studied when it is in equilibrium with soil water – all soil water potential measurements are based on this principle. If an object comes into hydraulic contact with the soil, the water potential of the object comes into equilibrium with the soil water potential (UMS, 2015). However, when a relationship between soil water content and soil water potential is studied, hysteresis has to always be taken into consideration. It is explained by different characteristics of dry and moisture surface. Some of submicroscopic pores are closed due to swelling and enlargement of pores size (Kutílek, 1978).

From classic physics two types of energy are known, such as kinetic and potential. When movement of water in soil is rather slow, it is kinetic energy but it is considered as negligible because this type of energy is proportional to the velocity squared. Potential energy is important in terms of determination of the state and movement of water in the soil. Potential energy in soil has high variability. Natural tendency of all mature in nature is to go from place with high potential energy to place with low potential energy and put it into equilibrium with surroundings. In the soil, water moves continuously in the direction of decreasing potential energy. Basically, the rate of potential energy decreases with distance of the flow (Hillel, 2004). Determining the absolute energy level of soil water is a difficult and sometimes impossible task. It is not necessary to know the absolute energy level of water to predict how it will move in soils and in the environment (Brady and Weil, 2008).

Soil water potential reflects the energy state of water in porous media and thus drives water movement. It is necessary to make a proper measurement if water dynamics in vadose zone is to be described. The energy state of soil water can be expressed as energy per mass of water ($J.kg^{-1}$), as energy per volume of water ($N.m^{-2}$), which is equivalent to pressure (Pa) or as energy per unit weight of water, water potential expressed as pressure head, with units of water column length (m), see in Table 5 Expression of soil water potential as weight is mostly used in vadose zone (Durner and Or, 2005).

Table 5. Units and common symbols for potential energy of soil water (adjusted according to Or and Wraith, 200, and Hillel, 2004).

Units	**Symbol**	**Name**	**SI unit**
Energy/mass	ψ	Chemical potential	$J.kg^{-1}$
Energy/volume	p	Soil water potential, suction or tension	$N.m^{-2}$ (Pa)
Energy/weight	h	Pressure head	m

Total soil water potential (ψ_t) is defined as the amount of work that an infinitesimal unit quantity of water at equilibrium is capable of doing when it moves (isothermally and reversibly) to a pool of water at similar standard (reference) state (similar pressure, evaluation, temperature and chemical composition) (Or and Wraith, 2002).

There exists equation of determination of total soil water potential, here expressed as the energy related to a unit mass of water, see Equation 4.

$$\psi_t = \psi_g + \psi_w + \psi_o + \psi_a + \psi_e + \psi_{pt} \tag{4}$$

Where (according to Or and Wraith, 2002):

ψ_t ....total soil water potential ($J.kg^{-1}$)
ψ_g ....gravitational water potential, vertical distance between the reference and point of question
ψ_w ....matric potential
ψ_o ....osmotic potential, presence of solutes in the water, can be neglected in non-saline soils
ψ_a ....pneumatic potential, if the air pressure in soil is different from the air pressure at the free water level
ψ_e ....envelope potential, if soil is deformed by outside mechanical pressure
ψ_{pt} ....groundwater potential, hydrostatic pressure of the groundwater column

3.3.4. Measurement of soil water potential

A variety of techniques for matric potential in the laboratory and in the field exist but fundamentally, there are only two highly precise ways to measure it, with a tensiometer or with vapor pressure. The tensiometer works in the wet range of soil water potential, which means from 0 to about -0.2 MPa. On the other hand vapor pressure methods work in the dry range of water potential thus, approximately -0.1 MPa to -300 MPa. According to current technology is possible to measure the full water potential range in the lab but a skilled user and excellent methods are needed (UMS, 2015). Table 6 shows soil matric potential sensors and / or soil moisture sensors which are used e.g. to assist with irrigation management to indicate availability of soil water for crops. Wetting front detector is another sensor type which is not commonly used. Soil matric potential is measured in units of pressure, most used unit is kPa. Soil matric potential is suction and its unit is negative (Thompson and Voogt, 2015).

Table 6. Soil matric potentials sensors (Thomson and Voogt, 2014).

Type of sensors	Format/comments	Manufacturer
Tensiometer	- manual version - visual data reading from manometer - electric version - connected to logger or programmer - microtensiometers	- Irrometer Company, Inc., USA - Many other manufacturers - UMS GmbH, Germany*
Granular matrix sensor	- hand-held reader - can connect to logger or programmer - most commonly used sensor is Watermark sensor	- Irrometer Company, Inc., USA
MPS-2 & 6 Water potential sensor	- used with data loggers - relatively new sensor	- Decagon Devices Inc., USA*

**UMS GmbH. and Decagon Devices, Inc. recently merged together and the combined company is named METER Group, Inc.*

Tensiometers are relatively cheap and simple devices, but they require proper maintenance and installation. Granular sensors are in general a bit less accurate than tensiometers but require far less attention (Thomson and Voogt, 2015).

3.3.4.1. Tensiometer

Water attracted to soil particles is an expression of matric water potential. Field tensiometers measure this attraction or tension. The tensiometer is a tube filled up with degassed water closed at the bottom with a porous ceramic cup, see Figure 4. Once placed into the soil, water moves through the porous cup to the soil until the water potential in the tensiometer is the same as matric water potential in the soil. As the water is drawn out, vacuum develops in the tube and can be recorded (Cassel and Klute, 1986; Brady and Weil, 2008). The level of pressure (tension) in the vacuum indicates how much energy is needed by a plant to overcome the strength with which the soil holds moisture. If the soil is near saturation, the pull of water into the soil from the tensiometer will not be strong. The tensiometer reading is accurate until air does not enter the tube, which means the stop of measurement (Hensley and Deputy, 1999). One of the most frequently used commercially available tensiometers is from Irrometer Company, Inc., USA. This device is installed in the ground with the tips placed at desired root zone depths. The drier the soil, the higher the gauge reading. An irrigation application or rainfall event reverses this action (Irrometer, 2017).

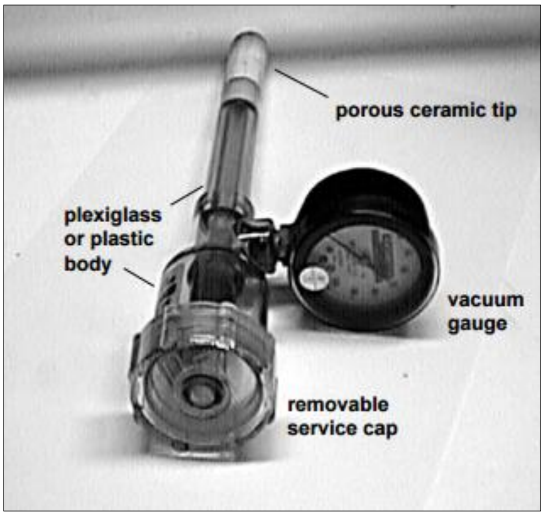


Figure 4. Tensiometer (Hensley and Deputy, 1999).

3.3.4.2.Granular matrix sensors

A granular matrix sensor (GMS) (Figure 5) has been developed for electronic measurement of soil moisture. The GMS measures soil moisture that can be converted to soil water potential by using a different calibration formula provided in the literature or calibrating them for specific soil type. The GMS can be used by irrigators to determine when and how much water to apply (Light et al., 1991). The sensor consists of a pair of highly corrosion resistant electrodes that are embedded within a granular matrix. This device is designed to be placed in the soil permanently and allows reading the data as necessary. Gypsum is installed in this sensor in order to provide some buffering for the effect of salinity levels normally found in irrigated agricultural crop s and fields (Irrometer, 2017). This soil moisture device has all desirable qualities such as low cost, maintenance and sufficient accuracy with range of 0 – 100 kPa. There is a few disadvantages of this device; firstly, the sensor does not respond properly to rapid drying and partial rewetting of soil which can lead to unreliable estimation of the soil water state, and secondly, GMS does not respond to changes at soil water potential greater than - 10 kPa, and therefore it may not be a suitable tool in case of irrigation practice which maintains soils with low tension (Marković et al., 2016).

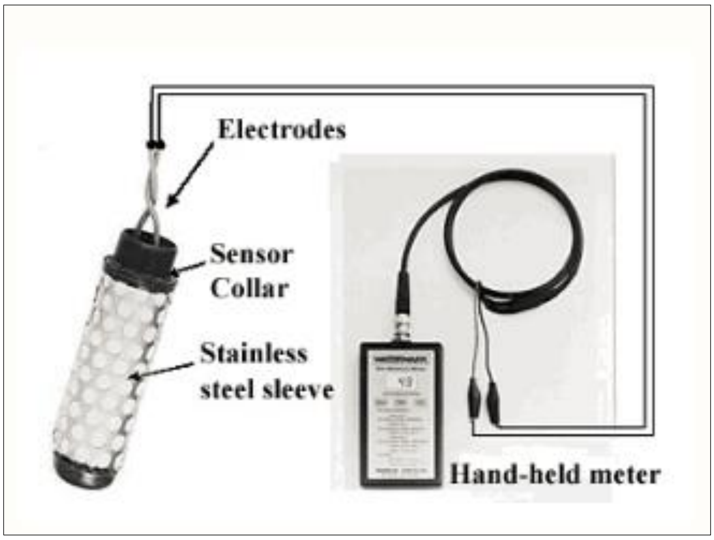


Figure 5. Granular matrix sensor by Irrometer Company, Inc. (picture taken from University of Nebraska, 2008).

3.3.4.3. MPS-2 and MPS-6 Dielectric water potential sensors

MPS-2 and MPS-6 Dielectric water potential sensors (Decagon Devices, Inc.; see in Figure 6) are used for measuring of soil or other porous materials matric potential and temperature. In principle, the water content of porous ceramic discs is measured and converted to matric potential using the moisture characteristic curve of the ceramic. Given that device needs a good hydraulic contact with the surrounding soil. The preferred method for installing the sensor is to take a native and wet soil, than surrounded the sensor with it. The sensor together with the moist soil is buried into the desired soil depth. Range for measuring the matric potential is from -9 to -100,000 kPa or may be expressed as pF 1.96 to pF 6.01. Accuracy of this type of device is +/- 25 % or 10 % of reading + 2 kPa, for MPS-2 or MPS-6, respectively, over the range from

- 9 to -100 kPa. On the other hand, laboratory evaluations have shown good accuracy and low sensor-to-sensor variability to at least −1500 kPa. This sensor does not require high power which makes it ideal for continuous measuring and periodic data logging. Temperature at which the device works is between -40 to 60 °C and relative humidity range is 0 to 100 %. MPS-2 and MPS-6 use a surface-mounted thermistor to take temperature reading. The sensor is possible to connect to a data logger, such as Em50 in order to make the reading easy. This device measures accurately only in case there is no exposure to any oil, therefore it is recommended to avoid any contact with skin oil, synthetic oils or any other hydrophobic compounds (Decagon Devices, 2016).

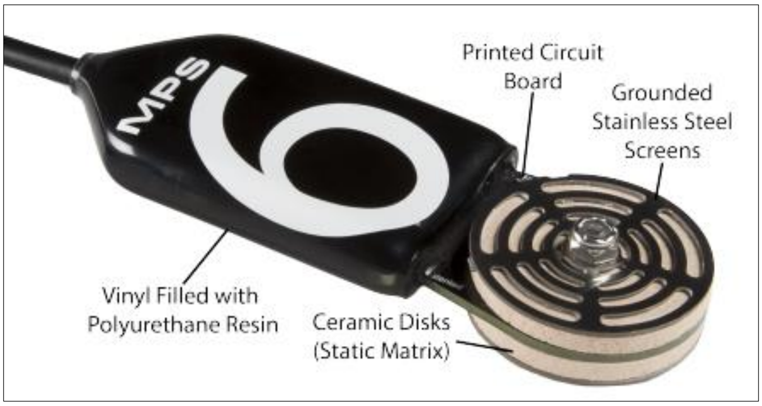


Figure 6. MPS-6 Water potential sensor (Decagon Devices, 2016).

3.3.4.4.Evaporation method and Hyprop Device

Measurement of unsaturated hydraulic conductivity is important for soil hydrological research. Many methods of measurement have been introduced over the last decades. One of them is evaporation method which was developed by Wind in 1966 and is applied as a standard method in many laboratories. This evaporation method has been modified. Tension measurement of two depths in a soil core and to measure the soil mass during the evaporation time is required. This method determines soil water retention curve and unsaturated hydraulic conductivity (Schindler and Müller, 2006). In a simple evaporation experiment, the pressure head at multiple heights and column weights are taken several times, until the tensiometers, which are used for pressure head readings, fail or weight change becomes negligible. Schindler’s method uses pressure head measurements in two different depths (Peter and Durner, 2008).

Commercially available Hyprop device (UMS GmbH., Germany) (see Figure 8) is based on the same principle – two precise microtensiometers measure water potential at different depths of the soil. The sample gets dry by natural evaporation. It is necessary to record changes in weight which means a proper scale is a must (UMS, 2015).

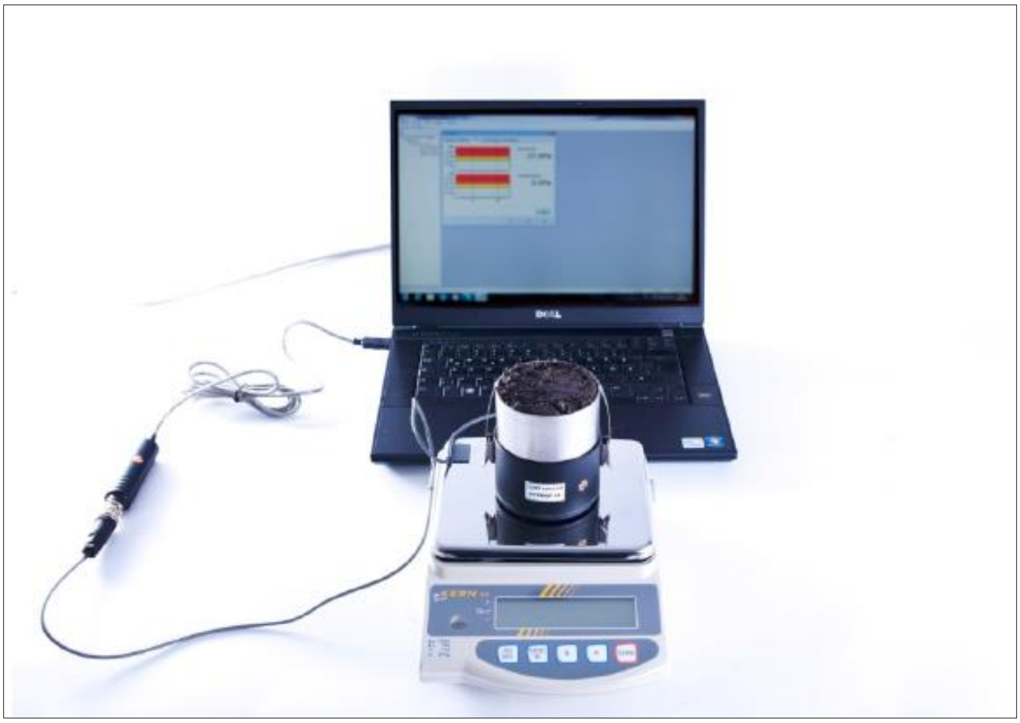


Figure 7. Hyprop device connected to computer with installed SW Hyprop view (UMS, 2015).

This device is used for laboratory evaporation method for determination of soil water retention curve and unsaturated hydraulic conductivity as a function of water tension or water content in a soil sample, and soil water retention curve. Microensiometers in Hyprop device have a measuring range from +100 kPa (water pressure) to -85 kPa (water tension). There are two sizes of microtensiometers – small (lenght 2.5 cm) and high (length 5 cm) – they pick up tension in two depths, Hyprop description see in Figure 8. When soil is too dry both tensiometers need to be refilled. Via the porous ceramic tip the soil water tension is conducted. The tensiometer shafts are one of the most sensitive parts of the whole system. Manipulation with this part of the system must be very gentle and with care. Important is to be aware of touching the tip of shaft to maintain water permeability and gas permeability. Tensiometers are not based on osmotic principle, the ceramic tip has a pore size r=0.3 µm and thus cannot block any ions (UMS, 2015).

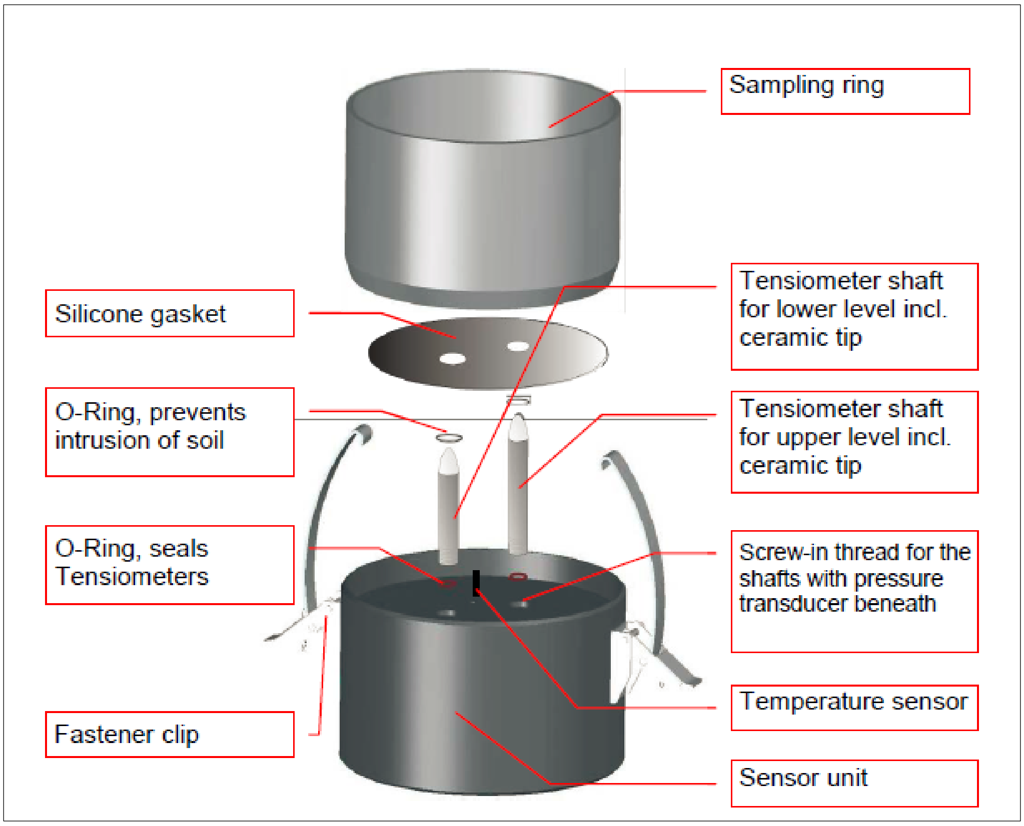


Figure 8. Hyprop device (UMS, 2015).

3.4. Hydraulic conductivity of soil

Saturated hydraulic conductivity (K_S) is one of the most important hydrophysical characteristics of soils. Its value is needed for different applications and it is a crucial input parameter for practical solutions in soil and water relationship, hydrogeology, soil and groundwater protection against pollution, environmental protection, irrigation and drainage for agricultural and non-agricultural purposes, and many others. It is also one of the main input parameters for simulation modelling of water, solutes and pollution transport through the soil profile (Oosterbaan and Nijland, 1994; Báťková, 2013).

Saturated hydraulic conductivity is defined as the constant of proportionality in Darcy's law (Equation 5).

$$v = K_s \cdot \frac{\mathrm{dh}}{dx} \quad (5)$$

Where:

v………..apparent velocity of the groundwater (m.d^{-1})

K_S……….hydraulic conductivity (m.d^{-1})

h………..hydraulic head (m)

x………..distance in the direction of groundwater flow (m)

In the vadose zone, unsaturated hydraulic conductivity rather than saturated takes place, as most of the natural processes involving the soil-water-atmosphere-plant interaction occur under unsaturated conditions of the soil. Unsaturated hydraulic conductivity as a function of pressure head K(h) or soil water content K(θ), is an important soil hydrophysical characteristic for solving problems in water management, agricultural water management or protection of the environment; infiltration capability of soil is determined mainly by soil pores geometry, which is determined by soil texture, structure, and other physical and chemical soil properties, including amount and quality of soil organic matter. Hydraulic conductivity in general is a property describing the ease with which water can move through the soil profile. Movement of water through the unsaturated soil profile is influenced by many factors; e.g. porosity of the soil and saturation of the soil profile. Changes over time are caused for example by crop and seasonal variability, irrigation practices, erosion processes and traffic-induced compaction of the soil. Another factor influencing the value of the measured unsaturated soil hydraulic conductivity is the initial water content of soil. The role of the initial soil water content in the determination of unsaturated soil hydraulic conductivity using a tension infiltrometer was studied i.e. by Matula et al. (2015).

Several methods exist to determine the K(h) relationship, preferably it should be measured in situ. No reference measurement method concerned with tension infiltrometer exists, however different types of disc infiltrometers have been designed and used (examples can be found in Báťková et al., 2013).

Measurement of saturated hydraulic conductivity in-situ may be affected by preferential ways occuring in the soil profile, such as earthworm paths, cracks etc. This influence can be reduced by measurement of unsaturated flow by disc infiltrometers. When the soil is unsaturated, a certain part of the pores is filled with air and the hydraulic conductivity decreases. By setting a certain pressure head on the soil surface during the measurement, the pores with lower air-entry value than the applied pressure head are excluded from the process of infiltration, and the water moves through the soil matrix rather than through the preferential ways. In general, with increasing pressure head (negative value) the number of pores involved in the process of infiltration decreases. The result of infiltration experiment is one point in K(h) function, thus several measurements for different pressure heads h can compose the the K(h) functional relationship (Císlerová, 1989; Matula et al., 2015).

Unsaturated hydraulic conductivity can be determined also in laboratory by employing the previously described evaporation method (Schindler and Müller, 2006) with using the Hyprop device (UMS, 2015). With measuring the matric potential in two different depths of the core sample (induced by the two microtensiometers, one shorter and another one longer) the hydraulic gradient can be determined. The mass decrease, registered by weighing the soil sample, is used to calculate the volumetric water content and the flow rate of the water. More details can be found in UMS (2015) and other literature.

3.5. Soil water retention curve

Soil water retention curve (SWRC) defines the relationship between soil water content (θ) and matric potential (h), it is graphically expressed set of their equilibrium states. The relationship is different for each soil. SWRC is an important hydrophysical property of the soil material. Each soil texture and structure has a unique relationship between soil water content and water potential. This relationship describes ability of a soil to hold water and the power with which water is held by that specific soil (Irmak et al., 2006). Water is readily available to plants (no crop stress) over a narrow range of matric potentials. For example in silt-loam soil, irrigation can be triggered at matric potentials between 100 to 120 kPa to avoid crop stress (Minasny et al., 1999).

SWRC is strongly hysteretic. The progress of dewatering of fully saturated soil differs greatly from moisturizing of the dry sample. These two main branches called primary drying curve and primary wetting curve. Between them scanning curves may occur (see Figure 9).

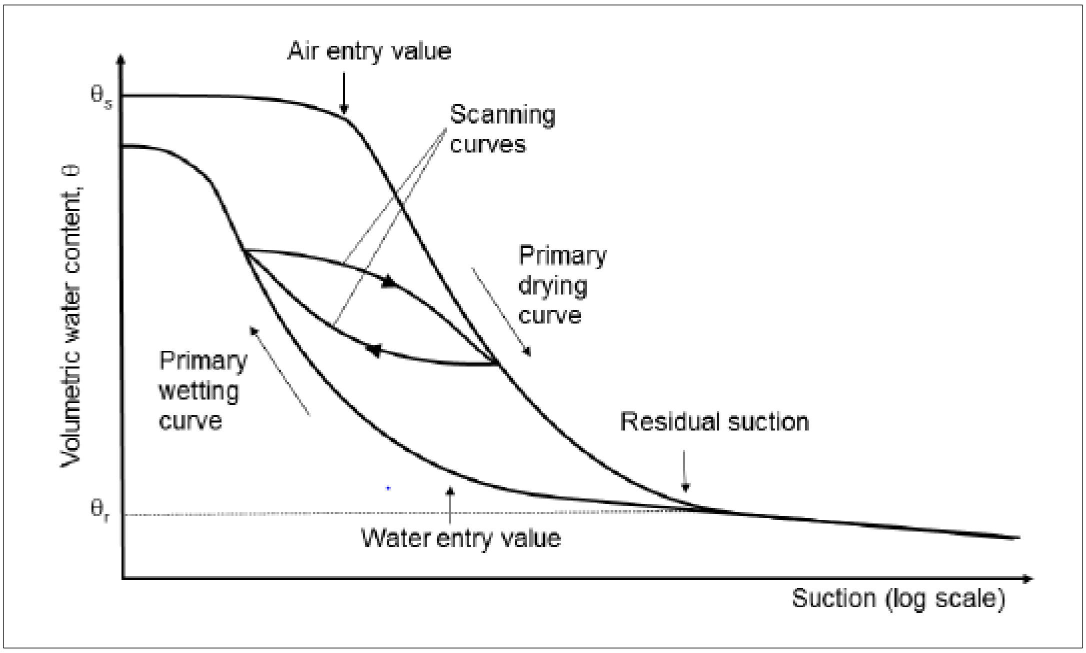


Figure 9. Hysteresis of soil water retention curve (Toll et al., 2015).

During rewetting of the dry sample, a situation when the sample will not be saturated up to the same original moisture level, but with less water in the sample than it was originally, might occur. Hysteresis is made (among others) by bubbles of air which are trapped in the so called blind pores. Influence of hysteresis is very often neglected (Kutílek, 1978).

There is a small issue – determining of this property can be costly and time demanding (Minasny et al., 1999), when using the classical laboratory methods such as combination of sand box and pressure plate device (Klute, 1986). But in situ measurement is time consuming, and inaccurate because of experimental shortcomings and temporal variability. Thus, the retention properties of unsaturated soils are often estimated indirectly from other soil properties – by employing pedotranfer functions.

Other physical properties, such a texture and structure affect soil water retention. There is a possibility to estimate soil water retention. Many attempts tried to define the soil water retention curve from different and easy measurable soil properties. In 1989 the term pedotransfer functions was introduced. Classical regression pedotransfer functions, which have been widely used for prediction of the SWRC may be divided into three types (Minasny et al., 1999):

1) Point estimation – at a pre-defined matric potential this function can estimate the water content. Often estimation of water contents are corresponding to field capacity (10 – 33 kPa) and permanent wilting point (at 1500 kPa), these points are necessary for determination of plant available water.
2) Parametric estimation – these pedotranfer functions are based on assumption that relationship between soil water content and matric potential can be described proportionally by a hydraulic model with certain number of parameters, such as e.g. van Genuchten model (1980).
3) Physico-empirical model – the water retention curve is derived from particle size distribution curve.

3.5.1. Analytical expression of soil water retention curve

A lot of soil and water management and environmental protection practices require knowledge of the water evolution in the subsurface. Many computer models have been developed over the last several decades. All these models tried to simulate water flow and contaminant transport in saturated and unsaturated soils. The application is very often restricted because of lack of hydraulic property information including soil water retention curve. Proper characterization and estimation of the soil water retention curve has been investigated for over

60 years (Ghanbarian-Alavijeh et al., 2010). There are many equations (such as Fredlund and Xing (1994); Kosugi (1996); Peters and Durner (2008) and others) but the most commonly used ones have been van Genuchen and Brooks and Corey analytical expressions of SWRC. Van Genuchten and Brooks and Corey parametric model are demonstrated in the Figure 10. Air entry value h_v in Brooks and Corey plotted line shoes where air goes into the soil and pores are filled by air. From 0 to h_v the relationship on the SWRC is linear than it becomes to be a curve (Persson, 2015).

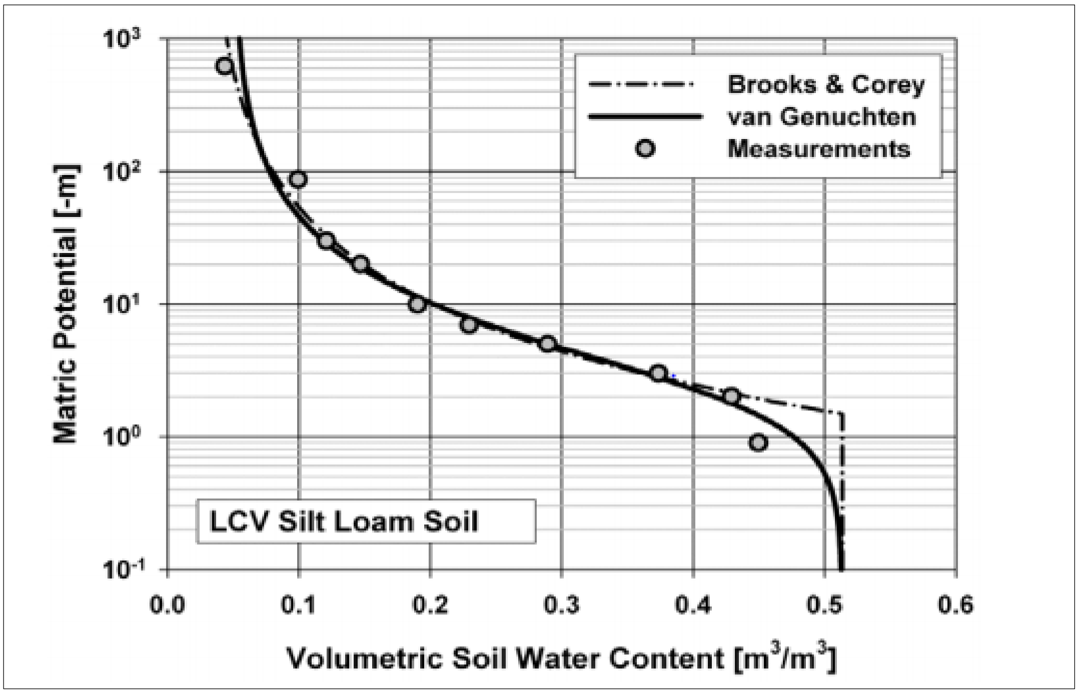


Figure 10. Van Genuchten and Brooks and Corey parametric models fitted to measured data for silt-loam soil (Tuller and Dani, 2003).

The empirical model of van Genuchten (1980), see Equation 6.

$$S_e = \frac{1}{[1+(\alpha h)^n]^m} \tag{6}$$

Where:

S_e ………effective saturation, calculated as $S_e = (\theta - \theta_r) / (\theta_s - \theta_r)$; θ = actual water content ($cm^3.cm^{-3}$), θ_r = residual water content ($cm^3.cm^{-3}$), θ_s = saturated water content ($cm^3.cm^{-3}$)

h ………pressure head, in absolute value (cm)

α……….empirical coefficient, reverse air-entry value (cm^{-1})

n, m……empirical parameters (n is between 1.5 – 6 and m is often setup as = 1 – 1/n)

Brooks and Corey (1964) equation has following form (Equation 7).

$$S_e = (\frac{h_v}{\mathrm{h}})^{\lambda} \qquad (7)$$

Where:

S_e ....effective saturation, as described above
h_v ....air entry value (represents “bubbling pressure”) (cm)
h ....pressure head (cm)
λ ....empirical coefficient, pore size distribution index (between 2 – 5)

3.5.2. Hydrolimits

Generally, hydrolimit is a certain volumetric water content soil achieved by precisely defined methodology. Most of the hydrolimits are not physically defined but in the Czech Republic they were often used due to their low price and faster measurement, compared to measurement of SWRC (Miháliková, 2011). The hydrolimits can be used for water storage estimation in the soil aeration zone in relation to plants. Soil aeration zone is one of the most important parts of the hydrologic cycle and it is one of the most complicated for water movement evaluation. Considering the fact that plants are supplied by water from the soil aeration zone, it is necessary to know the amount that the soil can provide to the plants. The water amount in the soil is dependent also on the weather changes during the long-term point of view. The hydrolimits can be found by various ways. One of the possibility is a laboratory assessment of hydrolimits values of the individual soil samples. Another possibility is use of water retention curves for reading of hydrolimits values for respective water potential (Štekauerová et al., 2002). Some hydrolimits are listed below (according to Miháliková, 2011).

Saturated water content (θ_s) – when all pores are completely filled with water it means soil is under saturated conditions. Practically it can be claimed, that it is equal to the soil porosity. In fact, the air is trapped in some parts of pores, therefore this value is lower than porosity.

Field capacity (FC) – soil moisture, which soil is capable of withholding water for the longer time after irrigation and infiltration into the profile. In the terrain, it is not possible to achieve equilibrium, it is a dynamic process, thus its determination has to be done approximately. It corresponds approximately to pF from 2.00 to 2.70. FC describes maximum moisture which remains in the soil from two to three days after the soil was irrigated. This value is dependent on dynamic properties of the soil profile, such as hydraulic gradient, hysteresis, stratification of the soil profile, swelling and shrinking, height of groundwater level or presence of impermeable layer.

Wilting point (WP) – is considered as a lower limit for the water availability for plants. It is soil moisture, in which the plants wither permanently. The roots have lower absorption than transpiration. The actual wilting point is dependent on the plant type, vegetation stage, meteorological factors, and osmotic pressure of soil solution. Therefore, it is in large range of values. Its determination can be done by pot experiment or by technical method.

Hydrolimits FC and WP are often associated with certain matric potential in order to simplify their practical use. These matric potentials varied in different countries. The available water capacity, which is the difference between FC and WP, is useful value in regional studies for irrigation intervals, classification and evaluation of agricultural production and landscape changes due to climate change. Table 7 shows the difference in the FC determination in the Czech Republic, the Netherlands, the USA and the United Kingdom (Miháliková, 2011).

Table 7. Field capacity and wilting point in different countries (Miháliková, 2011).

Hydrolimit	**Country**	**Log h (pF)**	**Suction pressure (bar)**	**Suction pressure (kPa)**	**Pressure head (cm H_2O)**
FC	**UK**	1.70	0.05	5	50
	NL	2.00	0.10	10	100
	USA	2.52	0.33	33	330
	CR	2.00 – 2.70	0.10 – 0.50	10 - 50	100 – 500
WP	**World**	4.18	15	1 500	15 000

(Note: simplified unit conversion used: 1 bar = 100 kPa = 1000 cm of H_2O)

In Table 8 are given some examples of field capacity and wilting points for different soil textures (Persson, 2015).

Table 8. Examples of field capacity and wilting point for different soil texture classes in the USA (Persson, 2015).

Textural class	**Field capacity ($cm^3.cm^{-3}$)**	**Wilting point ($cm^3.cm^{-3}$)**
Clay	0.40	0.25
Silt	0.35	0.15
Loam	0.30	0.10
Sand	0.10	0.05

4. MATERIALS AND METHODS

4.1. Biochar

Biochar which was used in this study was obtained from company Biouhel CZ, s.r.o. In February, 2017 this company got from the Central Institute for Supervising and Testing in Agriculture a certification for biochar as a supplementary soil substance as a first in the whole Europe. Mentioned biochar is sold under the tradename agrouhel®. Biochar is made by mixture of silage maize rests in a biogas station digestate and wheat straw in proportion approximately 1:1 (Biouhel.cz, 2017). The biochar was pyrolyzed for 18 minutes at 460 °C. The fresh biochar had water content by mass of 0.84 $g.g^{-1}$ and dry bulk density of loose uncompacted material around 0.15 $g.cm^{-3}$ (Kidane, 2016). Biochar used at the current study had water content by mass approximately 55 %; it was determined by gravimetric method. Two different concentrations of the biochar were tested and a blind control in addition. The selected biochar concentrations were based on practical applications onto agricultural fields suggested by previous studies found in literature. The concentration 0.1 % or 0.001 $g\text{-}g^{-1}$ (biochar dry matter to air dry soil actually) roughly corresponds to the application rate about 3 $t.ha^{-1}$, and the concentration 1 % or 0.01 $g.g^{-1}$ roughly corresponds to the application rate about 30 $t.ha^{-1}$, which meets the recommendation of the for field and gardening application, respectively. However, the actual biochar concentration in the field application depends on several factors, mainly the actual depth of ploughing and dry bulk density of the soil, which is changing during the vegetation season. For that reason, the added amount of biochar to different soil types with different proposed bulk densities remained the same. Calculated estimation of the biochar concentrations is given in Table 9. For more information, see Appendix A.

Table 9. Estimation of used biochar concentrations.

Sample labeling	**1**	**2**
Biochar concentration	0.1 %	1.0 %
Depth of ploughing (m)	0.22	0.22
1 ha area (m^2)	10000	10000
1 ha ploughing layer soil volume (m^3)	2200	2200
Approx. dry bulk density ($g.cm^{-3}$)	1.14	1.14
Corresponding ploughing layer soil mass per 1 ha (kg)	2508000	2508000
Biochar application rate ($t.ha^{-1}$)	2.6	26
Estimated biochar concentration ($g.g^{-1}$)	0.00104	0.01037
Mass of dry biochar added to 1 kg of soil (g)	1	10
Prepared biochar concentration ($g.g^{-1}$)	0.001	0.01

4.2. Description of soils used for experiments

For this study three representative types of soil were used with different physical and chemical properties. As a reference soil silica sand was used. Two other soils were taken in the experimental fields which belong to the Czech University of Life Sciences Prague, in Prague Suchdol and in Prague Uhříněves. Both soils – from Uhříněves and from Suchdol - were topsoils, A_p horizon. The fields were under intensive agricultural cultivation, the soil was taken in late summer 2016 after harvest, when the soil was bare.

4.2.1. Silica sand

Sand is white and has fine texture with diameter of particles in range 0.25 – 0.125 mm. Commercial name of this sand is ST 56. Abbreviation ST means Sport Top because this sand can be used for sport surfaces, mainly for equestrian sport where are given standards for the optimal surface. Sand is produced by the Czech company Sklopísek Střeleč, a.s. This company offer a wide range of different kinds of sand. Sand used for purpose of this study contains high amount of silica (silicon dioxide) with content of 98.9 %. Particle density of this reference soil is 2.65 $g.cm^{-3}$.

4.2.2. Luvisol - Uhřívěves

The second soil used for purpose of this study was soil from Uhříněves which is a luvisol formed on loess in semihumid climate. Department of Crop Production of CULS Prague has the experimental station in Uhříněves. This station is situated at 295 m a.s.l. Average annual temperature there is 8.4°C and average sum of precipitation is 575 mm (Capouchová et al., 2015; Dvořák et al., 2015). This soil has high nutrient reserve, texture class is clay loam, and organic matter content is 1.74 – 2.12 % (Tomášek and Dvořák, 2009). Luvisols together with Cambisols are the most widespread reference soil groups in Central Europe. Estimated soil loss in eroded Luvisols is about 0.5 – 0.6 m. Luvisols are the main soils associated with Cambisols (Świtoniak et al., 2016).

4.2.3. Chernozem – Suchdol

Last soil used for the experiment was soil from Experimental Terrain Station of Soil Moisture Dynamics of the Department of Water Resources in Prague Suchdol, Czech Republic with coordinates 50°8'N, 14°23'E. Field is located 286 m a.s.l. and climate here is moderately warm and moderately dry, mild winters prevail. The average annual temperature is 9.1 °C and precipitation 495 mm. Soil which occurs on this field is loamy carbonate haplic chernozem, land was used as arable. The total organic carbon content is approximately 2.5 % of dry matter (Doležal et al., 2012). Chernozem which can be found on this field is soil dark brown or black color, due to its enrichment of high-quality humus down to the depth of more than 40 cm, mostly 60 to 80 cm. Development of chernozem began as early as the late glacial period, and they were fully developed by the Atlantikum age. In Cetntral Europe chernozems and soil like chernozem make up about 3 % of the surface area and 5 % of the arable land (Altermann et al., 2005).

4.3. Sample preparation

All samples were artificially prepared by repacking core samples. After bringing the soils from the selected localities to the laboratory, big clods were gently crushed by hand and noticeable particles of the soil skeleton, plant and animal residues were removed. Soil was sieved through 8 mm sieve prior to further processing. The sieved soil was stored in laboratory conditions in big vessels, evaporation was not prevented, so the soil was air-drying slowly. The purpose of this procedure was to maintain the soil structure aggregates as natural as possible.

For preparation of repacked soil samples a process of homogenisation is necessary. If samples are not prepared carefully, each can have heterogeneous character and the reason why undisturbed soil samples were not taken instead of repacked vanishes.

The soil was properly and carefully mixed with naturally moist biochar (in amount recalculated to dry matter) by quartering method in order to prepare the intended biochar concentrations. Concentration 0 had no added biochar, in concentration 1 and 2 biochar was added, see Table 10. Soils of each concentration of biochar were stored in plastic bags.

Table 10. Explanation of biochar concentrations.

No. of concentration	**Concentration (g.g^{-1})**	**Added dry matter of biochar**
0	0.000	0g per 1500 g of soil
1	0.001	1.5 g per 1500 g of soil
2	0.010	15 g per 1500 g of soil

For each soil the three concentrations of biochar were used and for every concentration at least 3 repetitions were done. Special markings were designed for given experiments, see in Table 11.

Table 11. Legend for marking.

Soil type - abbreviation	**Origin of abbreviation**	**Soil type**
SA	Sand	Graded sand
UH	Uhříněves	Luvisol
SU	Suchdol	Chernozem

All samples were coded as follows; firstly No. of concentration, then soil type abbreviation and last number is number of repetition.

Example: **0SA3**

Where:
0 ……….concentration
SA……....sand
3 ……….third repetition

For measuring the retention curves on Hyprop device, Kopecky´s rings with volume of 250 ml were used, with 8 cm in diameter and 5 cm height (UMS, 2015).

Most of all laboratory studies of granular soil behavior require tests results based on homogenous and repeated studies. Samples preparation in the laboratory has been made by many different ways. One of them is to prepare soil sample by saturation, others can use dry or moist soil. Majority of soil sample preparation using a moist tamping technique. This technique has high effectivity because it provides homogenous sample and discourage segregation of the components and provide great control of sample density (Ibraim et al., 2012).

The moist tamping technique was used in this study as well. Weighed amount of air-dry soil was sprinkled by tap water and gently mixed before repacking, in order to not destroy the natural soil aggregates. Soil was just moist, not very wet. Approximately the same amount of water was used for spraying the soil, in order to keep the same initial water content as a starting point; however, small differences are possible. Each sample was prepared carefully to not lose any part of weighted amount of soil. Samples were compacted layer by layer directly to the core rings equipped by geotextile attached with rubber band. Special attention was focused on the constant dry bulk density. Dry bulk density was chosen for each soil based on previous experience and natural field dry bulk density.

Completed soil samples were ready for saturation, see on Figure 11. The whole procedure can be seen in Appendix B. Prepared sample must be protected against extreme temperature, direct sunlight and air currents. All analyzed samples should be as fresh as possible (UMS, 2015).

Figure 11. Prepared Kopecky´s ring with pure biochar.

Sand as reference material was used as a first soil, with target dry bulk density 1.4 g.cm^{-3}. 350 g of sand was used, for calculation of dry bulk density see Equation 3. Sand initial water content was selected as 10 %, therefore 25 ml of water had to be added (directly, without spraying, as sand does not have any structure). Luvisol and chernozem were prepared based on target dry bulk density 1.14 g.cm^{-3}, thus only 285 g of soil was used for one sample preparation. Biochar which is on Figure 11 was gently compacted in naturally moist condition without any target dry bulk density, which was then determined as 0.20 g.cm^{-3}.

Particle density of each soil was determined in laboratory according to standard water pycnometer method (CEN ISO/TS 17892-3) and calculated by using the following Equation 8:

$$\rho_z = \frac{m_s}{V_s} = \frac{m_s}{(m_1 + m_s) - m_2} \qquad (8)$$

Where:

V_s………volume of the soil particles without pores (cm^3)
m_s………mass of the dry soil sample (g)
m_1………mass of the pycnometer filled with water (g)
m_2……....mass of the pycnometer filled with soil sample and water (g)

Particle density for the pure biochar was also determined experimentally by employing the water pycnometer method (Figure 12), with using ethanol instead of distilled water due to hydrophobic properties of biochar. The final particle density of biochar was determined as 1.097 g.cm^{-3}.

Figure 12. Pycnometer method for determination of particle density of biochar.

Total soil porosity P is calculated as follows (Equation 9):

$$\mathrm{P} = \frac{\rho_z - \rho_d}{\rho_z} \qquad (9)$$

Where:

ρ_d……..dry bulk density (g.cm^{-3})

ρ_z……...particle density (g.cm^{-3})

Used sampling core rings tare masses were weighted prior to soil compacting. Geotextile and rubber band used for experiment were weighted as well. However, masses of all geotextiles and rubber bands were very similar, thus average of 5 representative rubber bands and geotextiles was made, therefore weight of 1.24 g per each rubber band and geotextile was used for further calculation.

4.4. Soil water retention curves measurement with Hyprop device

Hyprop device employing the evaporation method was used for SWRC measurement (UMS, 2015).

Hyprop is very sensitive device, therefore every part used for measurement has to be prepared with special attention.

When the soil samples were prepared they were saturated by capillary rising for about 24 hours and then the water level was increased to the top of the sample, for approximately 20 minutes, which was enough to saturate the soil sample and not to destroy the artificial soil structure.

While soil samples were saturating all Hyprop components had to be vented for later measurement. The microtensiometers, which are called also the tensiometer shafts (length 25 and 50 mm), are one of the most sensitive parts of the system. The tensiometer tip is made of porous ceramic Al_2O_3 and the special manufacturing process guarantees homogenous porosity with good water conductivity and it is more durable than conventional porous tip. The tensiometers have to be always handled with care. The soil water tension is conducted via the porous ceramic tip to the water inside the shaft and measured as an analogue signal by the pressure transducer (UMS, 2015).

If the soil gets dry and the cavitation point was reached, the tensiometers need to be refilled. Hyprop shafts should never be filled from inside. To avoid that air is trapped inside the ceramic the water must flow in one direction only from outside to interior. There are two possibilities how tensiometer can be refilled – with vacuum pump or refilled manually, both methods were used for purpose of this diploma thesis. Samples 0SA1 – 1SA3 were refilled manually, which is very physically difficult and time-consuming. The detailed procedure is described in UMS (2015). Moreover, venting of them were not satisfactory enough. Hence, refiling plexiglass components for venting were designed and manufactured during the work on Hyprop experiment. These components (Figure 13) were inspired by commercially produced refilling kit from UMS company, and they will be available for the future experiments at the Department of Water Resources.

Figure 13. Tensiometer shafts attached to refiling plexiglass components, which were manufactured especially for this experiment.

In order to vent Hyprop sensor units they were flushed out with distilled water and acrylic attachment for sensor unit was tacked to the Hyprop sensor unit. When it was tacked together, acrylic attachment for sensor unit was filled with distilled water up to the top of it and the entire assembly was connected to the vacuum pump as shown in Figure 14. The whole assembly was vented at least 5-6 hours, rather longer than shorter time.

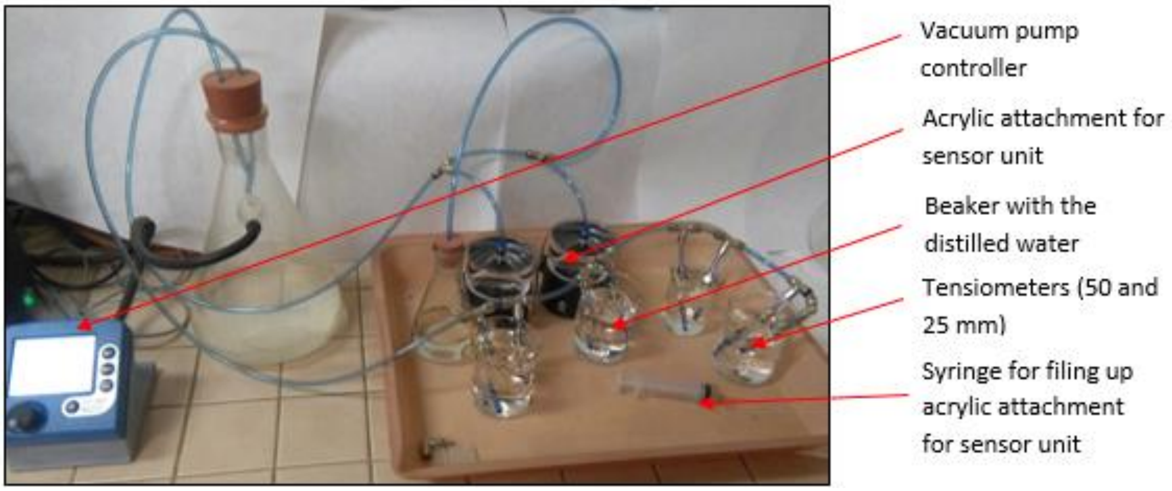
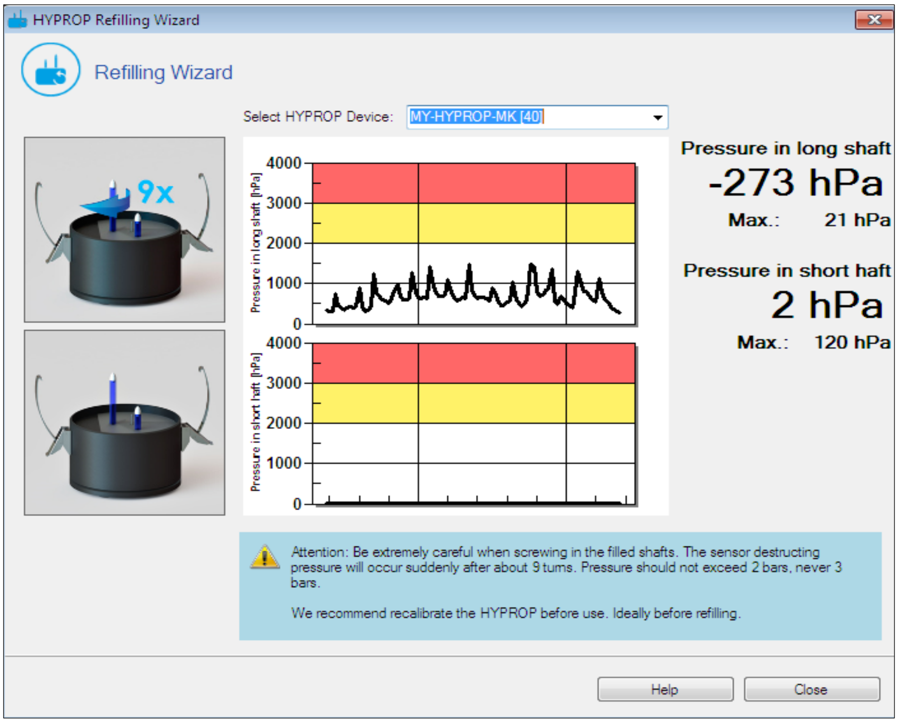


Figure 14. Vent of all components for Hyprop use.

When all needed components were properly vented they were connected together. Tensiometers were screwed into the Hyprop sensor unit. In order to not damage them, Hyprop sensor had to be connected to the computer and operated by Hyprop Refilling Wizard, which is part of Hyprop View software. The pressure was observed during the screwing the tensiometers into the Hyprop sensor unit on the screen of connected computer and it should never reach the red part of the given graphs, see the black line on Figure 15.

Once the tensiometers were successfully screwed into the Hyprop sensor, silicone protection cap was added and the sampling ring with prepared saturated soil sample was placed on the sensor unit and fastened with two clips. The sensor unit contains also another sensor which measures temperature for the whole time of measurement.

While everything was done the whole assembly was ready to start the measurement. The Start Measurement Wizard in Hyprop View software was opened and all important information about the measured sample were written, see Figure 16. Afterwards, registering of changes in soil matric potential and mass of the sample induced by evaporation started.



Select HYPROP Device: MY-HYPROP-MK [40]

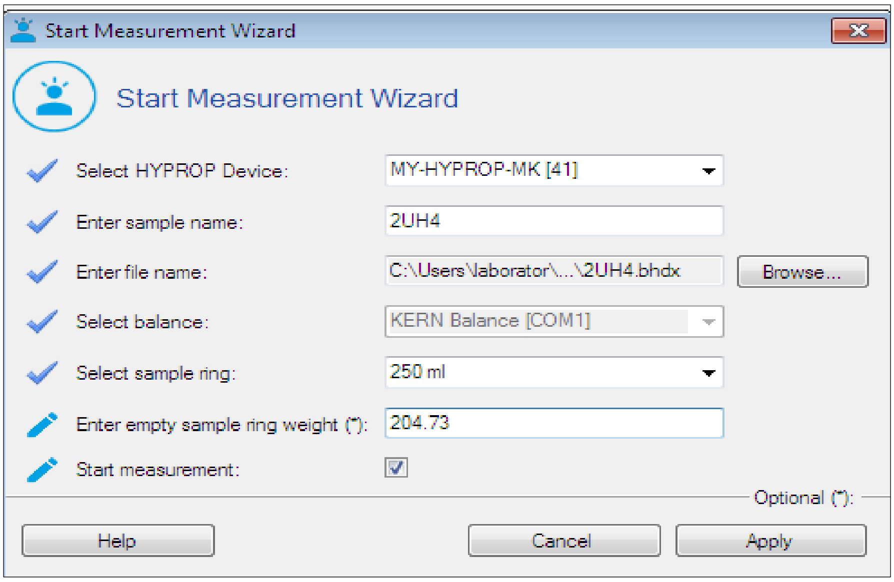
Pressure in long shaft
-273 hPa
Max.: 21 hPa

Pressure in short haft
2 hPa
Max.: 120 hPa

Attention: Be extremely careful when screwing in the filled shafts. The sensor destructing pressure will occur suddenly after about 9 turns. Pressure should not exceed 2 bars, never 3 bars.

We recommend recalibrate the HYPROP before use. Ideally before refilling.

Figure 15. Hyprop Refilling Wizard. The longer tensiometer shaft is just being screwed in.



Select HYPROP Device: MY-HYPROP-MK [41]
Enter sample name: 2UH4
Enter file name: C:\Users\laborator\...\2UH4.bhdx
Select balance: KERN Balance [COM1]
Select sample ring: 250 ml
Enter empty sample ring weight (*): 204.73
Start measurement: ☑
Optional (*):

Figure 16. Start Measurement Wizard.

All assembly during measurement can be seen in the Figure 17.

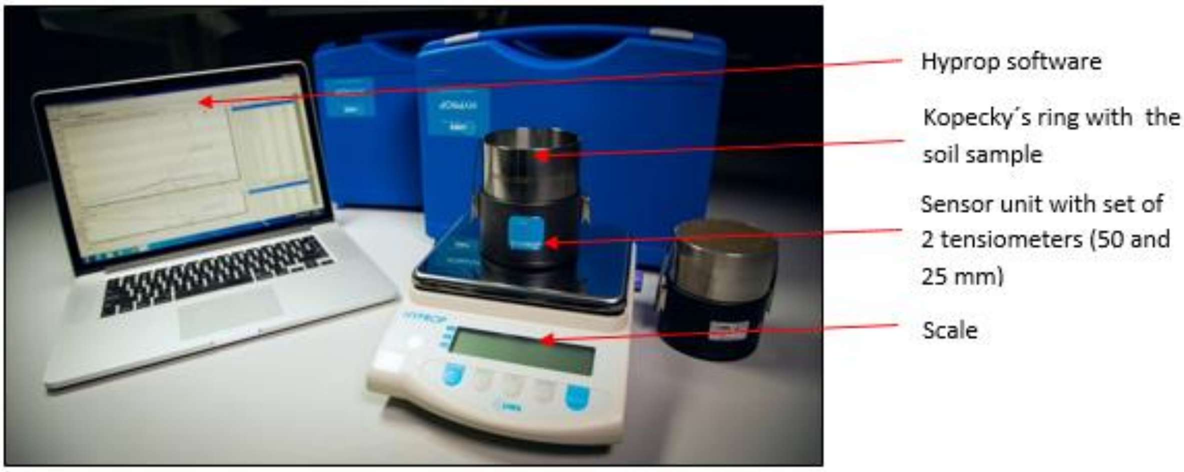


Figure 17. Hyprop device description (adjusted from UMS, 2015).

There are 2 to 3 samples (potentially up to 20, if sensor units would be available) which can be connected and measured at the same time. Hyprop view software offers two modes in which measurement can run. First, one Hyprop unit per one balance, where measured soil sample is permanently placed on the balance and measurement of tension and weighing goes at the same time at the given intervals. The second mode is more Hyprop units per one balance, in this case is possible to measure more soil samples at the same time. In the second case, all Hyprop units are places out of the balance, while connected to the computer. Measurement of tension is being registered continuously in given intervals. Nevertheless, when more samples are measured at the same time, weighing has to be done manually. Recommended interval for weighing is every 12 hours and the weight changes in between are reliably interpolated (as described further). For weighting on the balance, the Hyprop sensor unit has to be disconnected from its cable, which is signal for the software to register the weight and weighing wizard appears on the screen, which leads the user through the weighing process which takes about 10 seconds in total, see Appendix C.

For the purposes of this diploma thesis, the second option was chosen, two maximally three Hyprop sensor units were used at the same time, but two samples prevailed due to problem with system settings. Measurement of one sample took 6.5 days in average; the average time from saturation to cavitation point of the longer tensiometer (which is reference tensiometer for retention curve determination) was 5.49 days (7 905.6 min). Some samples could not be used because they were not approved for the measurement due to reasons such as poor venting of tensiometers, thus 34 measurements were done in total but only 29 were valid. The measurement period lasted from September, 2016 to February 21, 2017.

The measurement was finished, when the cavitation point of the tensiometers was reached (that means, air went through the ceramic cap into the tensiometers). End of measurement is recognized by sudden fall of tension, see the bottom picture in Appendix D. Hyprop View program was terminated and data were exported into an Excel file which were further processed.

The next step was to remove soil from the Hyprop sensor unit into the ceramic bowl. Sand is easy material to remove but luvisol and chernozem are soils with property to swelling and shrinking, therefore they were sticked to tensiometers and Kopecky´s ring and in order to not damage them, they had to be immersed into water upside down and soaked. All soil from all parts of Hyprop sensor unit was carefully washed to the ceramic bowl and dried in oven at 105 °C to the constant mass in order to determine the mass of dry soil for calculation of real dry bulk density.

4.5. Interpolation of soil samples weights

Weighting of the samples during the Hyprop measurement was done manually, recommended interval for weighting is every 12 hours but in this study weighing was done according to time options. Sometimes weighting was more frequent sometimes less frequent, especially during the weekends. Since the masses declined almost linearly with time, it was easy to interpolate the drop of weight. Firstly, the weight drop was recalculated to actual water content by volume, then a graph of decreasing actual water content depending on time was plotted in MS Excel. The data were very precisely fitted by polynomial equation of higher order (from 3rd to 6th, according to the best fit), see Appendix E. Usually a combination of two fitted equations was used for each graph, because the weight drop typically turned smaller close to termination of the measurement.

The trendline equations from the graph were then used to calculate the water contents corresponding with matric potential increase, which was registered every 30 min.

5. RESULTS

All measurements were carried out in the laboratory of Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources. In total, three soil types were used and three biochar concentrations for each of them with minimum three repetitions. Pure biochar was measured as well. The results were registered and evaluated.

Core samples were prepared to the target dry bulk density and weighed to determine the initial water content and saturated prior to the measurements of SWRC. Saturated water content was determined from first measurement on Hyprop device, at the beginning of evaporation process. Finally, the soil samples were dried in the oven at 105 °C to the constant mass and weighed. The real dry bulk density of each sample was calculated.

5.1. Physical properties of the tested soils

As an example, in the Table 12 are shown physical soil properties for zero concentration of sand which were obtained by weighting of Kopecky´s ring, freshly prepared sample, tare of ceramic bowl itself, and dry soil sample. Then the values of initial water content (θ_i) (Equation 1) and dry bulk density (ρ_d) (see Equation 3) were calculated.

Table 12. Example of data for zero concentration of sand.

No. of sample	**Tare of Kopecky´s ring (g)**	**Mass of prepared sample (g)**	**Mass of dry sample + bowl (g)**	**Tare of bowl (g)**	**Number of Hyprop unit**	**θ_i ($cm^3.cm^{-3}$)**	**ρ_d ($g.cm^{-3}$)**
0SA1	205.82	579.31	706.46	357.22	39	0.0920	1.397
0SA2	206.24	580.26	701.28	352.32	38	0.0953	1.396
0SA3	206.18	579.43	698.58	349.00	40	0.0897	1.398

Particle density of each soil was determined by water pycnometer method and used for calculation of soil porosity (P), see Table 13.

In the table the target porosity is presented, however, the real porosity was slightly smaller, as the real dry bulk density was slightly smaller due to small soil losses during preparation of the sample (some soil remained sticked to the bowl or packing tool). Keeping constant the dry bulk density was one of the important tasks of this study in order to focus on the effect of biochar on SWRC. The real dry bulk density of the measured samples compared to target dry bulk density is presented on Figure 18 the differences are not statistically significant.

Table 13. Measured physical characteristics of tested soils.

Type of soil	**Measured ρ_z (g.cm^{-3})**	**Target ρ_d (g.cm^{-3})**	**Target P (%)**
Sand	2.650	1.40	47.17
Luvisol	2.645	1.14	56.91
Chernozem	2.635	1.14	56.74
Pure biochar	1.097	0.20	81.61

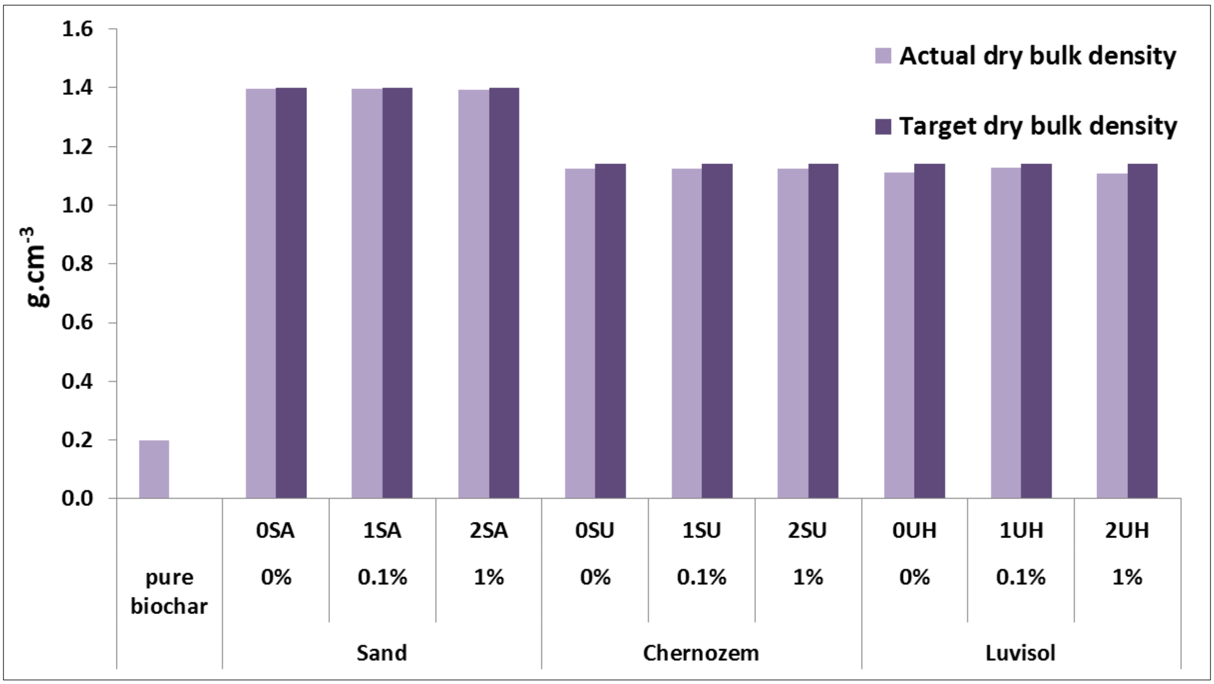


Figure 18. Comparison of actual and target dry bulk densities.

The initial water content of prepared samples before saturation, the calculated real porosity and saturated water content taken from first reading of Hyprop measurement are compared on Figure 19. Differences in initial water content are small, which shows on careful preparation of the samples. Saturated water content was observed always smaller than porosity. Average maximum degree of saturation (which is calculated as ratio of volumetric water content, here saturated water content, to porosity) was 88 % for sand and luvisol and 90 % for chernozem. It shows the ratio of pores filled by water to all pores. The degree of saturation of pure biochar was 88.9 %. The degree of saturation is always less than 100 % within soils saturated by capillary forces only. The average degree of saturation for Czech soils is 89 % (Miháliková et al., 2013). However, luvisol and chernozem samples were sometimes over-compacted, the sampling ring was not completely full there was about 2 – 3 mm empty space, which probably caused the higher difference between porosity and saturated water content.

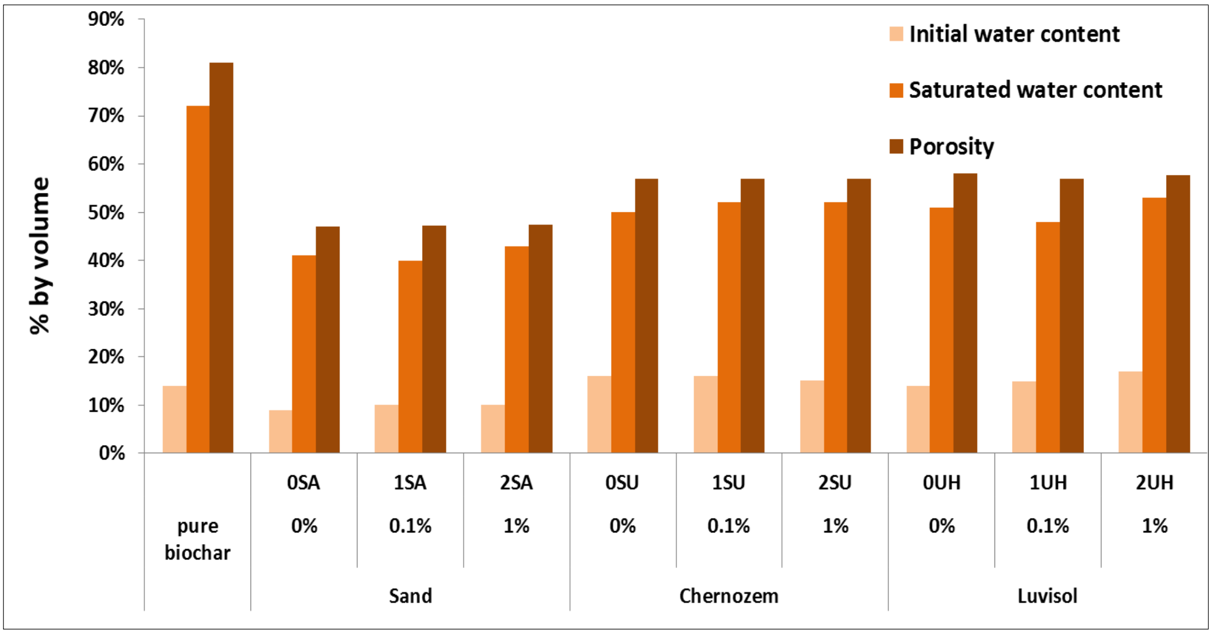


Figure 19. Comparison of physical characteristics of tested soils.

In the Table 14 are given main features from Hyprop measurement. Average days of measurement was 5.49 days. In average 3 samples were measured at the same time. Temperature was registered during all measurements, as it can influence the process of evaporation. Minimum and maximum values show how big differences occurred within each measurement, which is also represented by coefficient of variation (CV). The CV eliminates the unit of measurement from the standard deviation of a series of number by dividing it by the mean of this series of numbers (Abdi, 2010). For the first part of measurement up to measurement of sample 2SA6 there is more less consistent temperature because measurement was done in a laboratory no. 020 with almost constant room temperature. Following measurements were conducted in another laboratory of soil physics (no. 4).

In the table can be seen, that maximum pressure head of bottom tensiometer (the shorter one) is mostly lower than maximum pressure head of top tensiometer (the longer one). It is probably caused by higher sensitivity of the body of the smaller tensiometer to keep the degassed state during manipulation with the tensiometers, thus they were usually cavitated earlier. Also, it is obvious where the plexiglass refilling components started to be used instead of manual venting. They were in use from zero concentration of Luvisol (0UH1) and measuring of maximum pressure heads shows much higher values.

In the last column are system numbers of Hyprop sensor units used. Here was one anomaly – 0SA2 was measured for 2 tries. Hyprop no. 38 stopped working and had to be renamed for Hyprop 41, both measurements were connected together and they were used for purpose of next evaluation.

Table 14. Summary data from Hyprop measurement

No. of sample	**Lenght of measurement (days)**	**Max. pressure head bottom tensiometer (hPa)**	**Max. pressure head top tensiometer (hPa)**	**Min. temperature (°C)**	**Max. temperature (°C)**	**Average temperature (°C)**	**CV of temperature**	**No. of Hyprop unit**
0SA1	12.62	755.08	144.04	18.74	20.83	19.31	0.02197	39
0SA2	10.77	173.19	1049.00	19.83	22.07	20.47	0.02644	41
0SA3	12.60	817.15	162.47	18.94	20.33	19.52	0.01951	40
1SA1	10.84	126.81	985.83	17.57	18.62	18.03	0.01278	40
1SA3	10.28	111.71	577.38	17.11	18.40	17.65	0.35325	39
1SA5	7.45	110.92	1381.32	17.24	19.82	18.04	0.05289	40
2SA1	10.73	132.44	826.24	17.45	19.30	18.04	0.03514	40
2SA3	10.32	130.22	1474.37	18.1	20.03	18.73	0.02681	38
2SA6	8.13	136.69	682.36	16.65	19.68	18.02	0.05774	39
0UH1	3.09	835.28	1218.89	17.85	20.77	19.06	0.04611	41
0UH2	3.27	1011.12	1748.53	17.13	20.21	18.40	0.05221	40
0UH3	3.18	770.09	1372.91	16.92	20.07	18.15	0.05304	39
1UH1	2.54	1015.92	1519.67	15.03	17.42	16.34	0.03469	40
1UH2	2.89	812.34	1078.69	15.53	18.01	16.64	0.03223	41
1UH3	2.95	706.23	931.11	16.59	19.03	17.44	0.03114	40
1UH4	2.61	841.59	1175.12	17.35	19.79	18.13	0.02899	41
2UH1	4.29	1175.71	1626.57	15.85	19.76	17.28	0.06107	40
2UH2	2.82	849.37	1106.25	15.23	17.51	16.34	0.03277	41
2UH3	2.81	1123.64	1811.17	14.61	16.96	15.79	0.03896	40
0SU1	2.99	950.16	1450.23	16.36	18.81	17.38	0.03823	40
0SU2	2.92	756.76	1475.09	16.71	19.15	17.75	0.04353	41
0SU3	3.52	773.18	1442.8	16.65	20.21	17.86	0.06338	40
1SU1	3.54	945.25	1327.7	17.19	20.11	18.35	0.04596	38
1SU2	3.24	1170.6	1625.42	16.06	19.01	17.38	0.04694	40
1SU3	3.43	1113.62	1525.88	16.97	19.64	18.19	0.04179	38
2SU1	3.30	880.74	1219.04	17.13	20.06	18.23	0.02817	38
2SU2	3.28	986.18	1365.58	16.37	19.59	17.57	0.04360	40
2SU3	3.36	852.83	1103.03	17.09	20.2	18.29	0.04021	41
Pure biochar	7.56	576.71	850.73	18.15	20.57	19.01	0.03061	41

5.2. Soil water retention curves of the tested soils

On the graphs below (Figure 20, Figure 21, and Figure 22) are presented SWRC for each soil and biochar concentration. For each soil there are given all samples and all concentrations in one graph for better overview of the biochar effect. The retention curves were measured up to pF around 3, that means, about 1000 cm pressure head. The measuring range is limited by the tensiometers. For determination of wilting point another device would have to be used (for example pressure plate device), which was not available during the thesis experimental period.

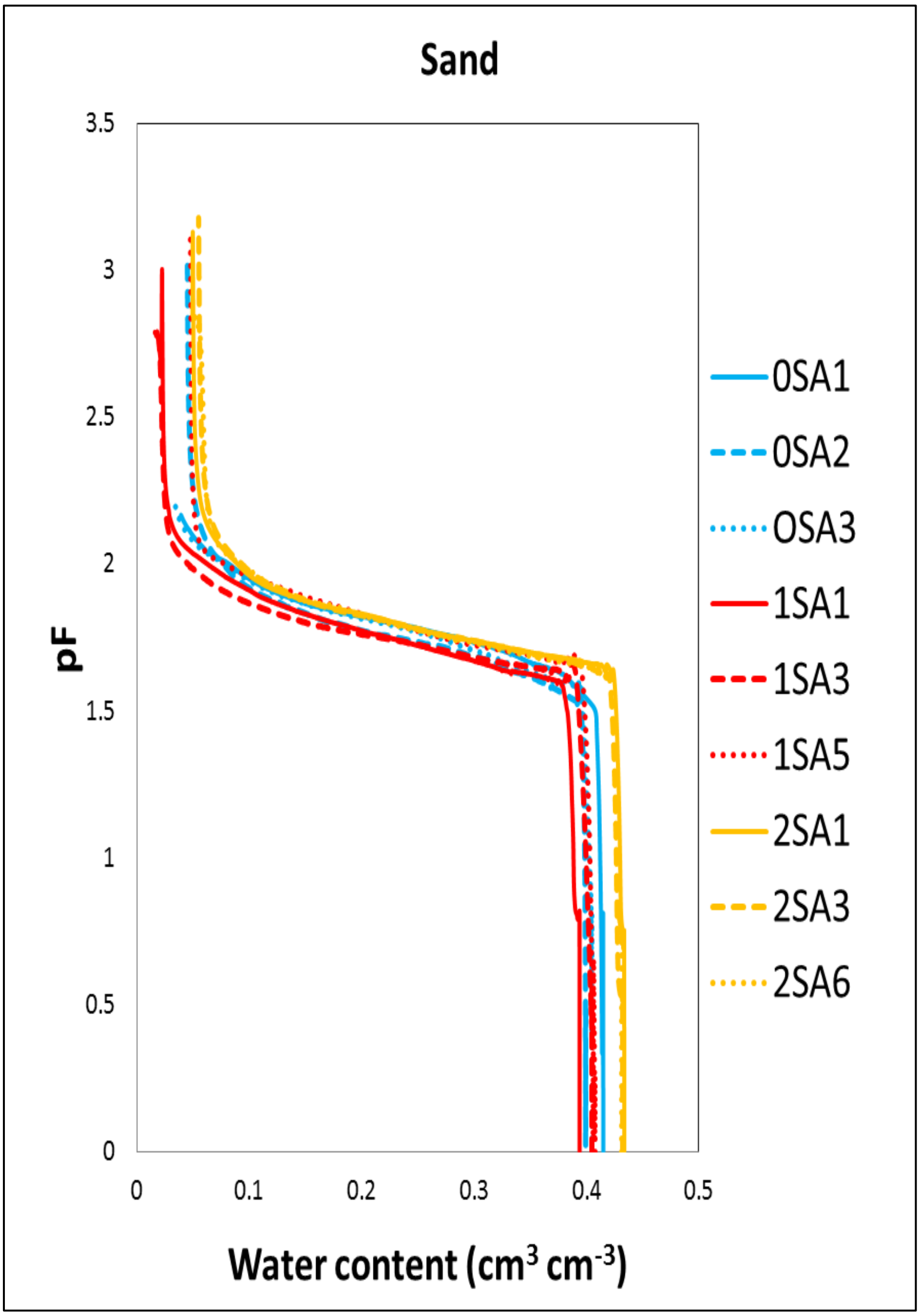


Figure 20. Soil water retention curves of silica sand.

An effect of biochar admixtures is visible on sand and luvisol soils, where the water content values are always highest for the higher biochar concentration (1 %). For these two soils, the lower biochar concentration (0.1 %) shows even smaller water contents than soil without any biochar. The chernozem does not show the differences very clearly, however, both biochar admixtures resulted in higher water content values. Luvisol shows higher effect of biochar close to saturation, while the effect on sand is in the same difference for the whole measured range of SWRC. Chernozem shows some biochar effect also close to saturation, while in higher tensions the effect of biochar is not observable at all.

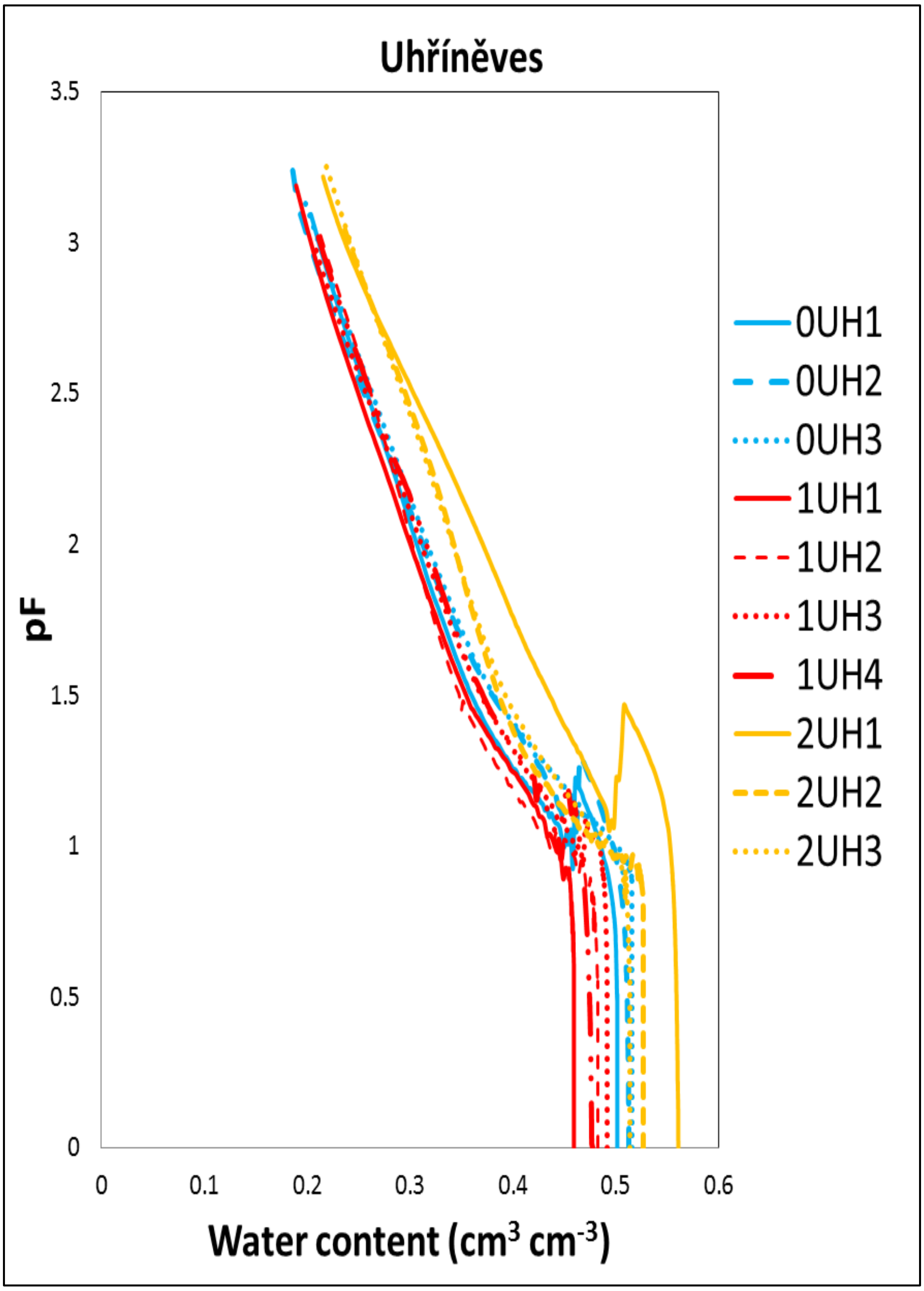


Figure 21. Soil water retention curves of luvisol (Uhřiněves).

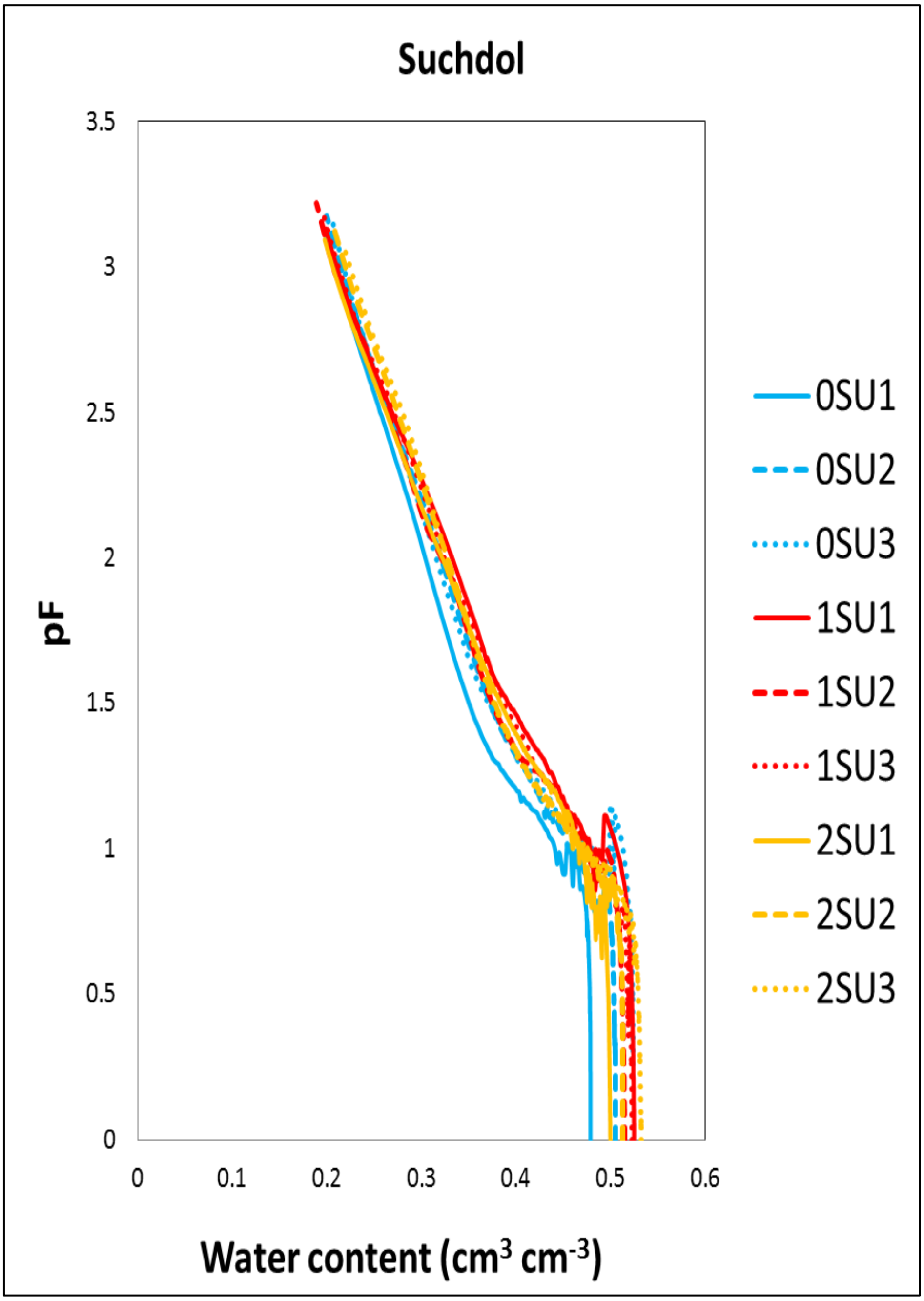


Figure 22. Soil water retention curves of chernozem (Suchdol).

The unique SWRC of pure biochar is presented on Figure 23. It has higher saturated water content than all tested soils and its measurement took rather long time when compared with all other samples. It took about 15 days, however, the top tensiometer cavitated at the 8th days of measurement and only the bottom tensiometer continued. More measurements of pure biochar would be appropriate, which were not conducted due to shortage of time.

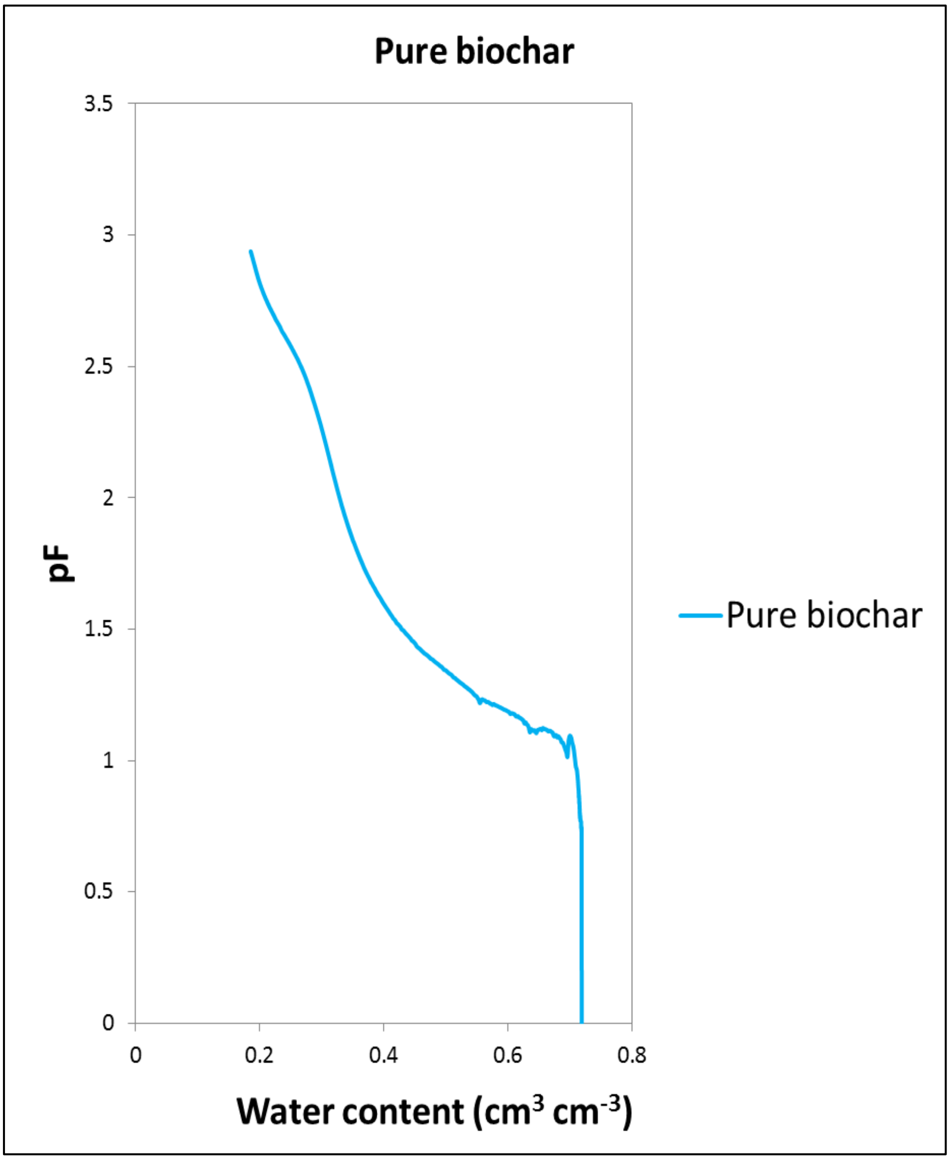


Figure 23. Soil water retention curve of pure biochar.

5.3. Statistical evaluation of biochar amendment on the soil

In order to statistically evaluate the effect of biochar amendment to each tested soil, some reference points for comparison had to be selected. Thus the saturated water content and field capacities at different pressure heads as defined by several countries were compared. The average of samples' repetitions was calculated for this purpose as an average of water contents at the given pressure head (50, 100, 336.1 and 501.2 cm, corresponding with field capacities defined in Table 7). Initial water content and dry bulk density were averaged and statistically evaluated as well.

T-test for independent samples was selected as the evaluating statistical tool. Statistical evaluation was made by SW Statistica 13.2 (Dell Inc., USA). Definition of t-test or Student´s test, a hypothesis test based on approximating the probability histogram of the test statistic by Student´s curve. T-tests usually are used to test hypotheses about the mean of a population when the sample size is intermediate and the distribution of the population is known to be nearby normal. This test can be used to determine if two sets of data are significantly different from each other (Helsel and Hirsch, 2002).

Number, which is closer to 1 (100 %) has the lowest difference. As closer to 0, as bigger difference. All results were evaluated at significance level P=0.05. The t-test matrices were built to compare differences between the effects of specific biochar concentrations on soil type and are summarized in Appendix F.

In initial water content θ_i evaluation can be seen no difference for sand chernozem and it proves that these samples were well-prepared. There is only a difference between concentration 1 and 2 for luvisol (UH). This difference might be caused by moisturing procedure because it was not exactly consistent, the samples were sprinkled 35 times from spraying plastic bottle.

For sand, in the whole measured range of retention curve 2SA has higher water content than 0SA and 1SA. Influence of biochar is statistically significant at saturation and then at pressure head h = 100 cm. Next pressure heads (336.1, 501.2) do not show such statistical differences and it can be explained that concentration 0 was not measured above pF 2 (h = 100 cm), therefore it is impossible to make reliable statistical evaluation. For luvisol, the statistically significant differences are observed in the whole measured range between 0UH and 2UH, and between 1UH and 2UH. The difference between 0UH and 1UH is statistically insignificant. For chernozem, no statistically significant differences were observed. The described reference points of SWRC are compared also graphically on Figure 24. The effect of 1 % biochar admixture is visible on sand and luvisol, and also the difference between sand and structured mineral soils. The SWRC of pure biochar differs obviously at the saturated at the saturated water content, but for higher tensions the difference between biochar and mineral soils is not significant, even it tends to hold less water in higher matric potentials than normal soil.

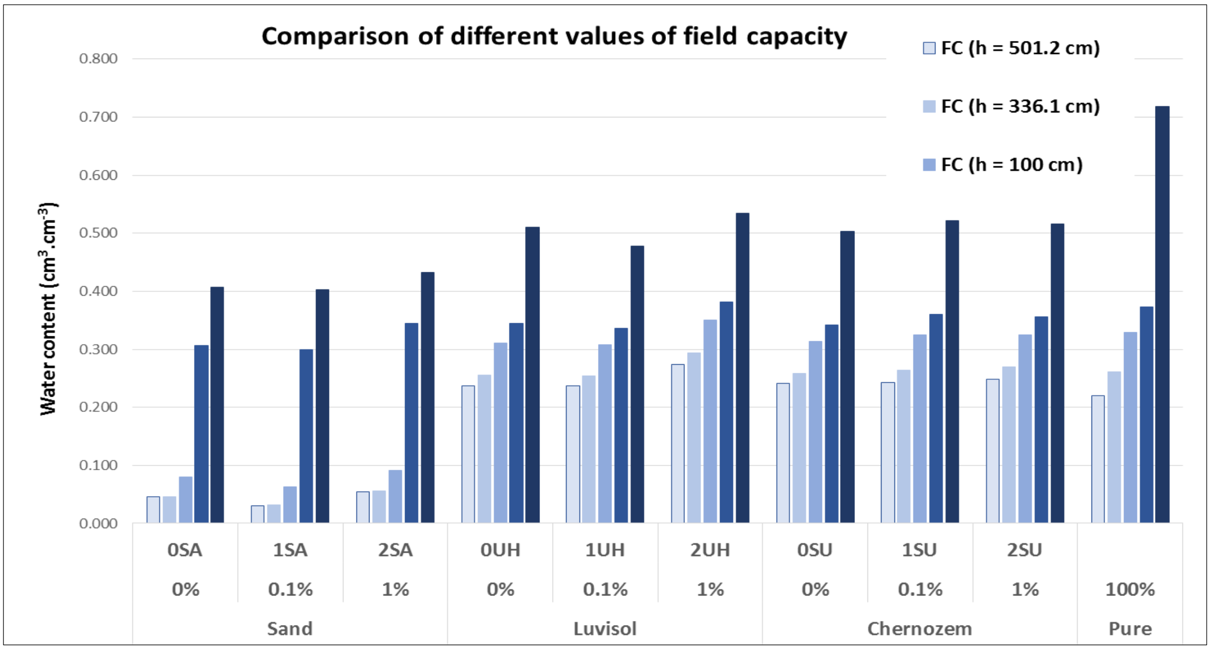


Figure 24. Comparison of reference points of SWRC for all tested soils and biochar admixtures.

The evaporation method used for determination of soil water retention allows also another type of comparison, and that is, time needed to reach a certain matric potential. For the same reference pressure heads as before, the times were observed and compared, as the biochar could effect the time needed to reach the field capacity. There are differences, as can be observed on Figure 25 however, the differences are not statistically significant at the significance level P=0.05. T-test matrices are listed in Appendix G.

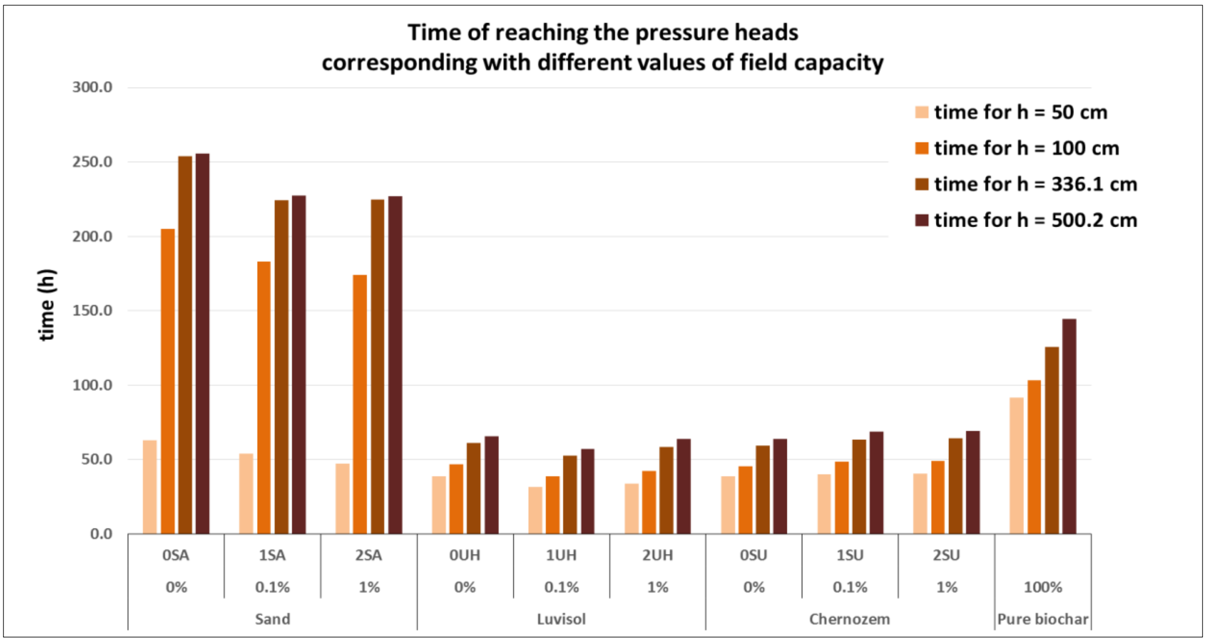


Figure 25. Time of reaching the pressure heads corresponding with chosen field capacities.

6. DISCUSSION

6.1. Irregularities in soil water retention curves

SWRC for sand (Figure 20) is without any anomaly, while in Luvisol (Figure 21) and Chernozem (Figure 22) retention curves can be seen some irregularities, “teeth”, which occur around pF = 1. According to Rivera (2017; pers. comm.) this is something that is pretty typical. It is right after the soil reaches the air entry point that is typically from a redistribution of water through the soil column. The second thing that causes this, is a physical phenomenon from the soil shrinking away from the soil core. When the soil breaks away from the edges of the core there may release energy that caused this shift in the matric potential. Both are fairly normal things that can be seen and they do not make a big impact on the fitting of the curve. These irregularities could not be observed by the traditional methods with limited amount of SWRC points such as sand tank or pressure plate device.

6.2. Impact of biochar to the soil water retention

Retention curves in chapter 5.2. show differences between each concentration. The biggest difference is between concentration 0 and 2. In the study of Liu et al. (2015) was observed that SWRSs of the biochar treated plots were significantly different from those of the controls. For his study hilly area in southern China with dominated loamy soil was used. Biochar which was used for this study was purchased from the energy company in China and was made from slow pyrolysis (at 500 °C).

Pühringer (2016) in his study writes that with increasing biochar rate in red clay loamy soil has been found significant difference in soil moisture for the biochar rate of 10 t.ha^{-1} and 5 t.ha$^{- 1}$ compared to the biochar rate of 0 t.ha^{-1}. However for the other tested soil – cambisols, there was no significant difference in soil moisture.

Castellini et al. (2015) reported that the impact of biochar on the soil water retention is widely documented. An increase in the soil water content or water holding capacity is generally expected for sandy soils amended with biochar but had no effect on loamy soil and decrease the moisture level in clayey soil. This finding suggests that soils with higher clay content are less likely to benefit from biochar addition s than coarser soils. Results of this study do not show such a difference. According to Huislová and Čechmánková (2017) the biochar affects positively the actual air capacity in the soil, which means, the soil water content decreased in fact. Soil with biochar (cambisol) showed about 3 % higher actual aeration in average compare to conventional variant. But 3 % is not difference at significance level. However, they underlined the positive effect on soil aggregate stability after 2 years of field experiment, which is important for prevention of soil erosion.

Hardie et al. (2014) found no evidence to suggest application of biochar influenced soil porosity by either direct pore contribution, creation of accommodation pores, or improved aggregate stability.

Hlaváčiková et al. (2016) investigated the effect of biochar on sandy loam soil with similar way as in this study, by mixing the soil with biochar and measurement of soil water retention curve. They investigated the biochar application rates 40 $t.ha^{-1}$ and 80 $t.ha^{-1}$, but they found small or no effect to the soil water retention.

Given studies prove that positive effect of biochar is not always obvious or observable immediately, and it does not depend only on added amount but also on its type and mainly on type of used soil. The effect of biochar seems to be small, however, when projected to appropriate numbers, it is not negligible. For example, the luvisol showed increase of soil water content slightly more than 3.5 % by volume in average. In the estimated ploughing layer of 22 cm (see Table 9), this water content means 0.035 multiplied by 220 mm, resulting in 7.7 mm of plant available water. For example, that is 77 m^3 of irrigation water per hectar saved.

During the measurement two interesting phenomena were observed, which deserve to be described in more details, as follows in next two subchapters.

6.3. Water repellency

Coarse-textured soils are more sensitive to the development of soil water repellency than finer textured soils (Doerr et al., 2009). A shortage of usable ground water has arisen not only because of the depletion of reserves salinization and pollution. Besides of these reasons there is another problem - greater drying of soils is making them less able to retain water. Water repellent barrier can form that limits that water cannot be absorbed. As the amount of water that can be exploited is declining, climate change models predict that soils will be much drier in summer months by 2017, mainly in northern temperate latitudes (Hallet, 2007). In the Figure 26 water repellency is evident. This effect was discovered accidentally. Two sand samples were regularly prepared for the following Hyprop measurement with about 10 % of initial water content. They were prepared in advance and left on the table in normal laboratory conditions for about 10 days. After that the samples were saturated firstly by capillary rising, but the water repellency was already observed. After immersing the samples to water almost to the top, the repellent behavior had not changed. The samples were then kept in water for several weeks, but without any change. The saturated hydraulic conductivity of these samples was measured by falling head device, but even after flowing the column of water through the samples, part of the sand around the ring remained completely dry and the water flew only through the middle part. The sample after this procedure with the lens of water on the top is presented on Figure 26 left. The right part of the picture shows the clear edges of the water repellent area. There were two samples one with lower concentration of biochar (0.001 g.g^{-1}) and the second one with concentration 0.01 g.g^{-1}. Higher concentration has proven higher water repellency. This phenomenon should be further investigated in future studies.

Šurda et al. (2013) describe development of water repellency on eolic sandy soil in western Slovakia. Biological soil crust is composed of mosses, algae, cyanobacteria, lichens and fungi covering the first millimeters of the topsoil. Organisms which are in the biological soil crust have an ability to produce chemical substances which can affect stability of soil surface, initiate soil erosion and decrease infiltration of water, mainly due to soil water repellency. Smaller K(h) values in the soil with biological soil crust can be measured by clogging of soil pores due to microbiologically produced polysaccharides (Šurda et al., 2013).

Figure 26. Biochar water repellency.

6.4. Impact of temperature to water retention curve of pure biochar measurement

Another interesting phenomenon was observed during the pure biochar water retention curve measurement. For the running measurement, the Hyprop View software plots two graphs with continuous values, one of them shows increasing the tension over time. The course of this curve is typical for different soil types. In this case, the measurement of the longer tensiometer collapsed around pressure head 800 cm, probably due to imperfect venting, and only bottom (short) tensiometer continued the measurement. At higher tensions (around 750 hPa, which corresponds roughly to 750 cm of pressure head) certain irregularities in the course of tension increment occurred. These irregularities were observed for 5 days approximately at the same day time, until the tensiometer also collapsed due to cavitation around 1450 hPa, see Figure 27.

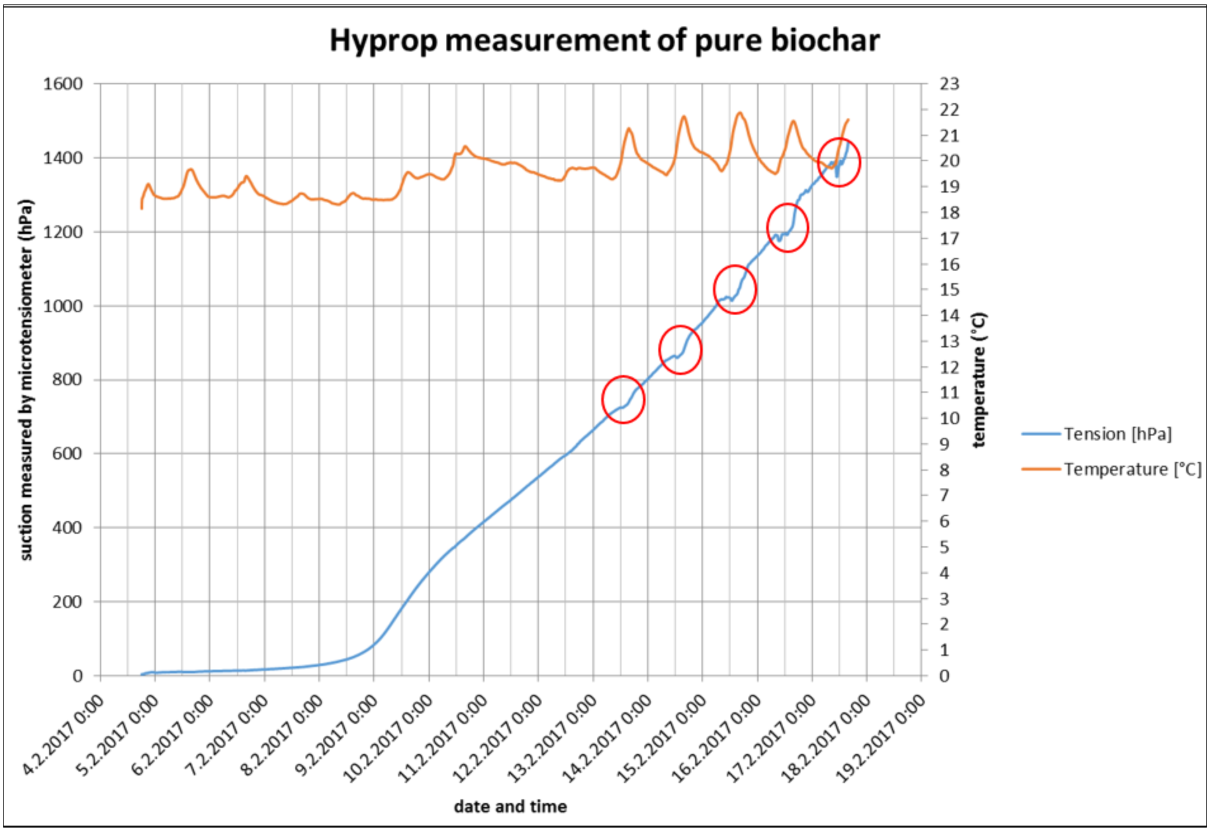


Figure 27. Irregularities observed during measurement of biochar water retention curve.

There is the idea, that the observed fluctuations might be in relation with temperature, thus the temperature measured inside the sample by Hyprop thermometer was plotted to the same graph. Fluctuations of temperature in the laboratory depend on several factors, such as heating system, outside temperature (a period of strong frosts occurred in the first half of February, 2017), sun directly shining to the lab room, running of oven in the same room etc. Unfortunately, the room temperature out of the sample was not observed.

However, the following observations can be described (compiled with significant help of my consultant and my supervisor):

a) Regular and steady increase in soil water tension (corresponding approximately to the average increase rate that could be observed when the temperature were constant at all times) is observed during the night between about 20:00 (8:00 PM) and 6:00 (AM). At this time, the biochar temperature is steadily decreasing but had not yet reached its minimum.

In order to better observe the phenomenon, the corresponding part of data was plotted in a normalized way on Figure 28. Let us assume that the process of quasi-steady dewatering (via evaporation in the Hyprop device) is superposable over the temperature dependent phenomenon we are interested in. The absolute difference in growth of the tension was plotted rather than the steady growth, and the temperature was plotted in such a scale to cover the tension differences. (In the graph, the tension or the matric potential is plotted in hectopascals as it was measured, thus it is denoted correctly as a suction pressure.)

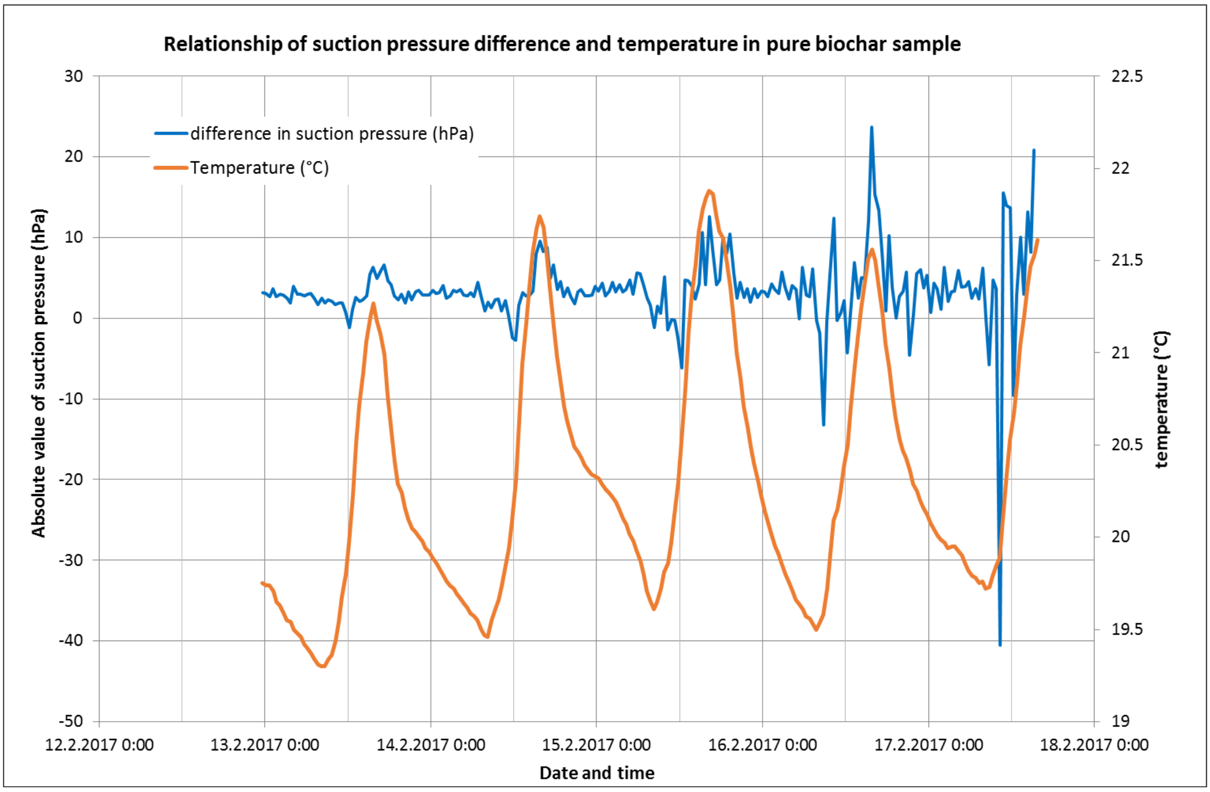


Figure 28. Selected part of suction pressure differences and temperature in pure biochar sample.

b) At about 8:00 AM the biochar temperature is at its minimum. Then it starts to rise. The period between about 6:00 AM and 12:00 PM (noon) is characterised by decline of the rate of soil water tension rise. At about noon time the soil water tension ceases to rise at all (the rate of rise undergoes oscillations around zero).

c) After the noon, the soil water tension starts to rise again (which is again accompanied by oscillations). The rate of the tension rise increases and reaches its maximum at about the same time when the biochar temperature reaches its maximum, which is at about 16:00 (4:00 PM). At this time the synchronicity of the temperature and the tension rise curves is most striking.

d) Then the biochar temperature starts to fall and the rate of the soil water tension increase starts to fall also (but the soil water tension as such goes on rising, albeit at slower pace) until about 20:00 (8:00 PM), when the “regular and steady rise” is re-established.

e) The whole effect only becomes apparent when the soil water tension rises (in the absolute value) above 700 hPa.

As a first approximation, the effect can be regarded as static. This means that dynamic processes, such as the water vapour condensation or the liquid vapour evaporation or quasi-periodic macroscopic movements of either liquid or vapour up and down, can be neglected within the sample (have only secondary importance). The static effect which is in work is mainly the dependence of the water-air-biochar surface tension and the corresponding contact angle on the temperature. In a simplified treatment, where these two dependences will be treated as one, assuming the contact angle (between biochar and water) to be zero (taking biochar as a hydrophilic material). Then the Laplace equation (see Kutílek et al., 2000) will be (Equation 10):

$$p_c = \frac{2\sigma}{r} \tag{10}$$

Where:

p_c……………additional pressure for a curvature of the water surface which is a result of work needed in order to extend the surface of a liquid film (Pa)

σ……………surface tension of water, which is $7.28 \cdot 10^{-2}$ N.m^{-1} at 20 °C. It depends on temperature; it decreases with increasing temperature.

r ……………radius of a meniscus in a model capillary tube (m)

If the soil water potential’s main component is capillarity (as it is in our situation), then (Equation 11):

$$h = -\frac{p_c}{\rho g} \tag{11}$$

Where:

h ……………..pressure head (m) as the expression of soil matric potential

p_c…………… additional pressure for a curvature as described above

ρ …………… density of liquid water (kg.m^{-3})

g ……………..acceleration due to gravity (m.s^{-2})

Based on these two equations, the increase in temperature of the system (water and biochar) will result in the decrease in surface tension σ, then in the decrease in the capillary pressure p_c according to (1), then in the increase in soil water potential (pressure head h) according to (3) (the absolute value of h will, of course, decrease).

So, the static theoretical analysis suggests that the tension (absolute value of matric potential) should decrease when the temperature increases. The actual decrease in tension occurs in the morning between about 6:00 AM and the noon.

After the noon, however, the temperature goes on rising until about 16:00 (4:00 PM), while the tension starts to increase. This is difficult to explain with the static theory and a dynamic theory must be used. We may raise the following hypothesis (but cannot yet prove it in an independent way): The sample of soil (biochar) is heated during the day from the air and the diffusion radiation in the laboratory. The wave of heating progresses from the top to the bottom. The temperature gradient so created causes the migration of water from the top to the bottom. The soil near the upper surface becomes drier and warmer. The tension of soil water in the upper part of the sample increases (in the absolute value). This process culminates at about 16:00 (4:00 PM). Then an opposite process takes place and makes the temperature decrease, while the tension declines to zero (if the average dewatering rate is substracted from it, which is reached at about 20:00 (8:00 PM)).

This phenomenon should be further studied in future studies.

7. CONCLUSION

This study was focused on the investigation of increasing soil water retention when biochar is applied. Two different biochar concentrations in addition to blind control were used on three different soil types. Evaporation method was employed for determination of soil water retention curves. Repacked soil core samples were used with focus on constant dry bulk density during the sample preparation.

It was hypothesized that application of biochar will enhance soil water retention. There was an assumption, that the higher the application rate, the higher will be the effect. In the beginning there were big expectations due to optimistic literature, that biochar will enhance water retention a lot. However, these expectations have not been fulfilled. Hypothesis was not fully confirmed. Although, smaller increase of soil water retention was observed, it is not statistically not significant. The biggest effect was observed on luvisol from Uhříněves, where the difference between control and 1 % biochar concentration in soil water content was about 3.5 % by volume in average in the whole range of measured SWRC. Thus, the hypothesis of increasing effect with increasing amount of biochar was confirmed.

The main objective of this diploma thesis was to determine and evaluate soil water retention curve of three different soils which were mixed with different amount of biochar in laboratory in sufficient number of replicates with specific attention to the dry bulk density of the soils. And the second one was to provide an assessment of the selected biochar. Both objectives were fulfilled.

Based on results recommendation for the future studies can be done. The SWRC were measured directly after mixing the soil with biochar, thus there was no time to re-develop the soil structure, thus the direct effect of intrinsic biochar properties was studied rather than an overall influence. Future studies should focus on long-term influence of biochar admixtures to the soil water retention.

During sample preparation for Hyprop measurement one phenomenon, water repellency of biochar was observed as a by-product. Suggestion for the future is to focus on biochar induced development of water repellency.

It can be also said, that influence of biochar concentration used for purpose of this diploma thesis was small. Thus, there is another suggestion for the future experiments – to use higher concentration of biochar. When higher concentration of biochar will be used, one question has arisen and it is if it is still environmental friendly and if it pays off economically. These things should be taken into consideration as well.

And last recommendation is to verify results of this diploma thesis by experiment which is running for longer time period and in the natural environment.

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9. APPENDICES

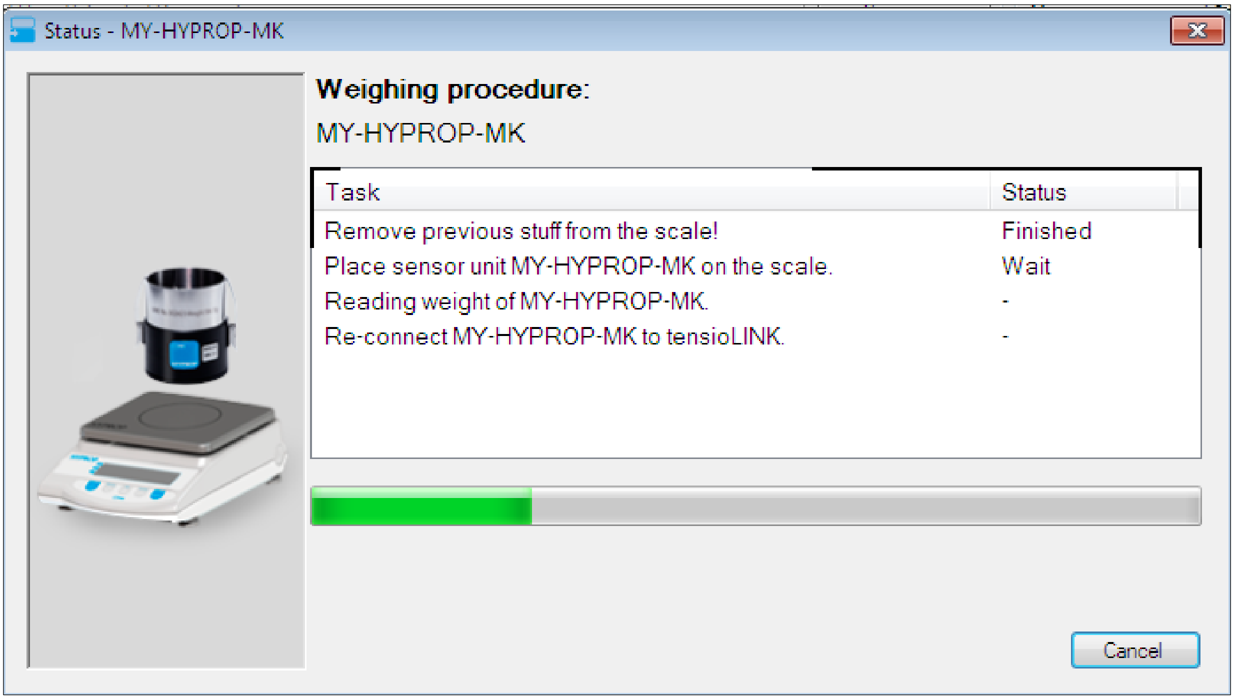
Appendix A. General properties of the tested biochar.

Characteristics	**Value**
Burnable matter in dry sample (%)	min. 45.0
Dry matter (%)	min. 60.0
Total carbon content as C in dry matter (%)	min. 45.0
Total nitrogen content as N in dry matter (%)	min. 1.0
Total phosphorus content as P2O5 in dry matter (%)	16
Total potassium content as K2O in dry matter (%)	17
Calcium content as CaO in dry matter (%)	56.3
Magnesium content as MgO in dry matter (%)	6.6
pH	9 – 11.0
Particles <2 mm (%)	min. 40.0
Particles >10 mm (%)	max. 10.0

(Source: http://www.agrouhel.eu/?page_id=8)

Appendix B. Sample preparation.

Appendix C. Hyprop view during the weighing of samples.

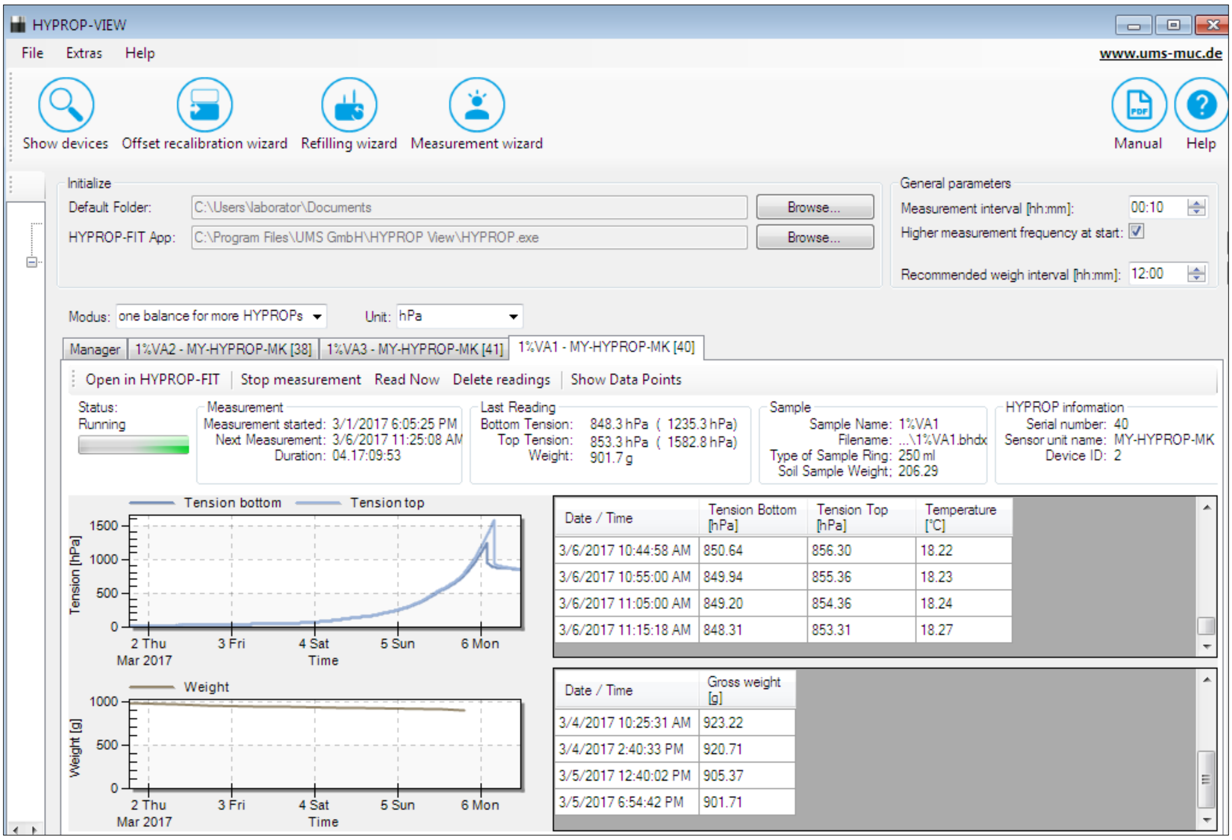


Weighing procedure:

MY-HYPROP-MK

Task	Status
Remove previous stuff from the scale!	Finished
Place sensor unit MY-HYPROP-MK on the scale.	Wait
Reading weight of MY-HYPROP-MK.	-
Re-connect MY-HYPROP-MK to tensioLINK.	-

Appendix D. Sudden fall of tension in Hyprop View.



Initialize

Default Folder: C:\Users\laborator\Documents

HYPROP-FIT App: C:\Program Files\UMS GmbH\HYPROP View\HYPROP.exe

General parameters

Measurement interval [hh:mm]: 00:10

Higher measurement frequency at start: ☑

Recommended weigh interval [hh:mm]: 12:00

Modus: one balance for more HYPROPs

Unit: hPa

Status:
Running

Measurement
Measurement started: 3/1/2017 6:05:25 PM
Next Measurement: 3/6/2017 11:25:08 AM
Duration: 04.17:09:53

Last Reading
Bottom Tension: 848.3 hPa (1235.3 hPa)
Top Tension: 853.3 hPa (1582.8 hPa)
Weight: 901.7 g

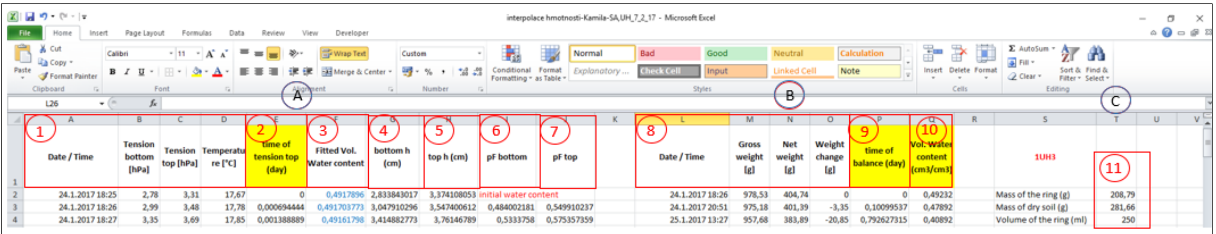
Sample
Sample Name: 1%VA1
Filename: ...\1%VA1.bhdx
Type of Sample Ring: 250 ml
Soil Sample Weight: 206.29

HYPROP information
Serial number: 40
Sensor unit name: MY-HYPROP-MK
Device ID: 2

Date / Time	Tension Bottom [hPa]	Tension Top [hPa]	Temperature [°C]
3/6/2017 10:44:58 AM	850.64	856.30	18.22
3/6/2017 10:55:00 AM	849.94	855.36	18.23
3/6/2017 11:05:00 AM	849.20	854.36	18.24
3/6/2017 11:15:18 AM	848.31	853.31	18.27

Date / Time	Gross weight [g]
3/4/2017 10:25:31 AM	923.22
3/4/2017 2:40:33 PM	920.71
3/5/2017 12:40:02 PM	905.37
3/5/2017 6:54:42 PM	901.71

Appendix E. Interpolation of weight; examples of the graphs.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	① Date / Time	Tension bottom [hPa]	Tension top [hPa]	Temperature [°C]	② time of tension top (day)	③ Fitted Vol. Water content	④ bottom h (cm)	⑤ top h (cm)	⑥ pF bottom	⑦ pF top		⑧ Date / Time	Gross weight [g]	Net weight [g]	Weight change [g]	⑨ time of balance (day)	⑩ Vol. Water content (cm3/cm3)		1UH3	⑪
2	24.1.2017 18:25	2,78	3,31	17,67	0	0,4917896	2,833843017	3,374108053	initial water content			24.1.2017 18:26	978,53	404,74	0	0	0,49232		Mass of the ring (g)	208,79
3	24.1.2017 18:26	2,99	3,48	17,78	0,000694444	0,491703773	3,047910296	3,547400612	0,484002181	0,549910237		24.1.2017 20:51	975,18	401,39	-3,35	0,10099537	0,47892		Mass of dry soil (g)	281,66
4	24.1.2017 18:27	3,35	3,69	17,85	0,001388889	0,49161798	3,414882773	3,76146789	0,5333758	0,575357359		25.1.2017 13:27	957,68	383,89	-20,85	0,792627315	0,40892		Volume of the ring (ml)	250

① Data transported from Hyprop fit

② Date of measurement - Initial date of measurement

③ Calculated from given Equation on chart

④ $\frac{\text{Tension bottom [hPa]}\,.\,100\,.\,100}{1000\,.\,9.81} \rightarrow$ from equation p = ρ . h . g (resp. $h = \frac{p}{\rho . g}$)

⑤ $\frac{\text{Tension top [hPa]}\,.\,100\,.\,100}{1000\,.\,9.81} \rightarrow$ from equation p = ρ . h . g (resp. $h = \frac{p}{\rho . g}$)

⑥ Decadic logarithm of bottom h in centimeters

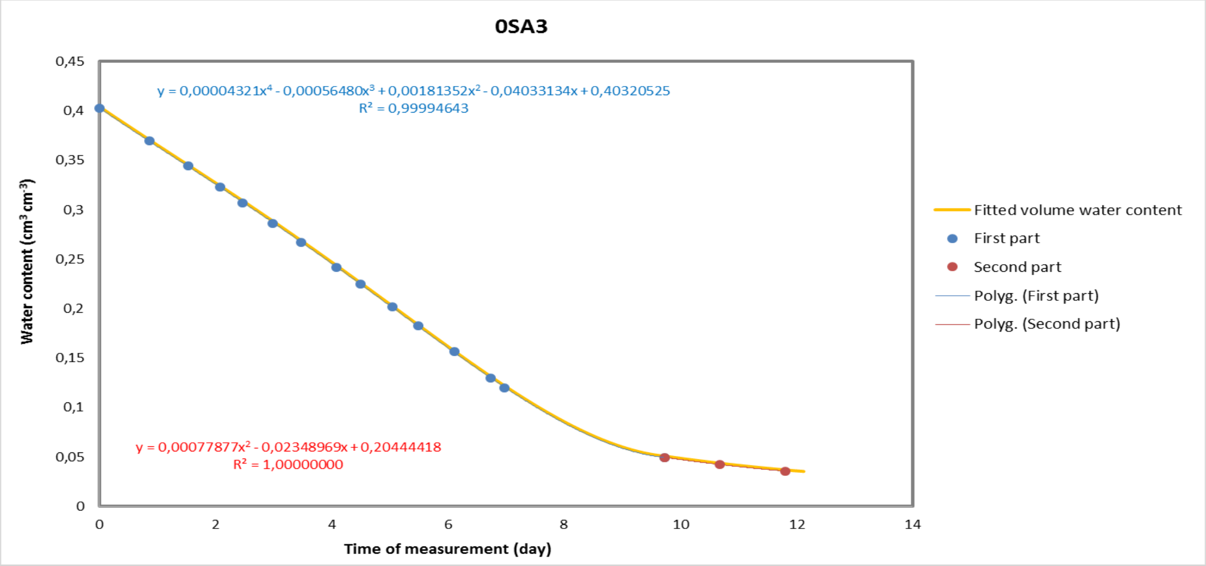
⑦ Decadic logarithm of top h in centimeters

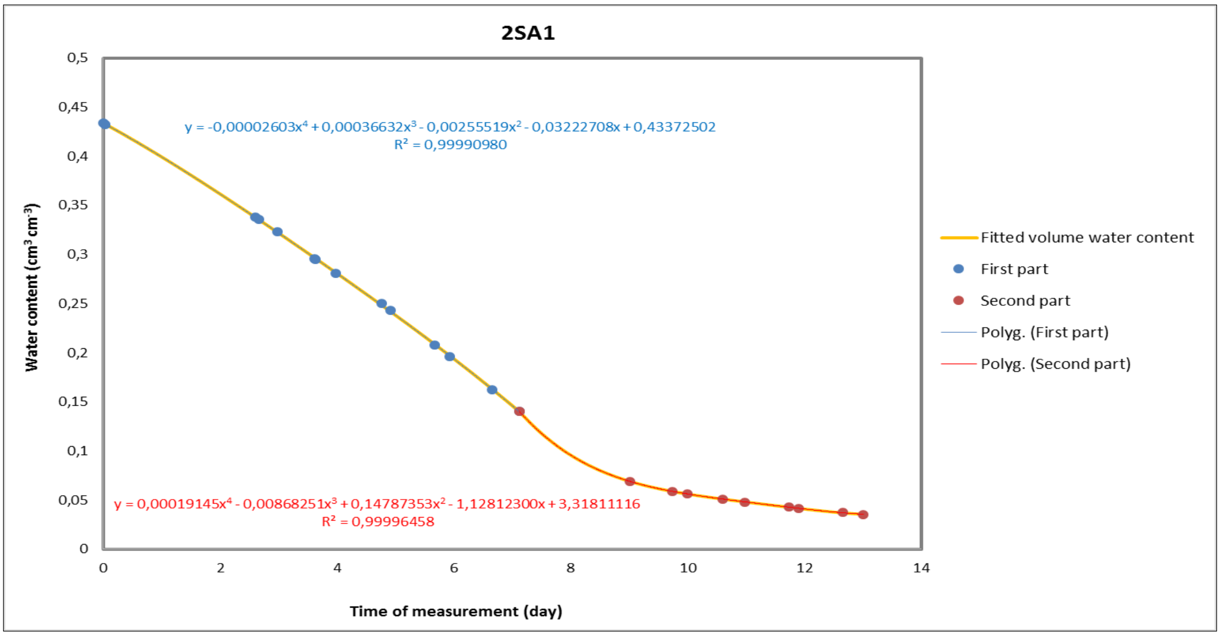
⑧ Data transported from Hyprop fit

⑨ Date of measurement - Initial date of measurement

⑩ Water content by volume $\theta = \frac{V_W}{V_S} = \frac{\text{net weight} - \text{mass of dry soil}}{\text{volume of the ring}}$

⑪ Mass of the ring: from weighting; Mass of dry soil: BD.volume of the ring





Appendix F. T-test for initial (θi) and saturated (θS) water contents, bulk density (BD), and chosen field capacities (for given pressure heads h).

θ_i	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.181	1.000							
2SA	0.340	0.626	1.000						
0UH	0.006	0.011	0.009	1.000					
1UH	0.000	0.000	0.000	0.650	1.000				
2UH	0.000	0.000	0.000	0.053	0.001	1.000			
0SU	0.000	0.000	0.000	0.274	0.056	0.031	1.000		
1SU	0.000	0.000	0.000	0.293	0.070	0.028	0.902	1.000	
2SU	0.003	0.005	0.004	0.763	0.993	0.060	0.387	0.416	1.000
biochar	0.003	0.015	0.011	0.768	0.634	0.090	0.411	0.452	0.901

θ_S	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.487	1.000							
2SA	0.004	0.002	1.000						
0UH	0.000	0.000	0.000	1.000					
1UH	0.000	0.000	0.002	0.015	1.000				
2UH	0.001	0.001	0.002	0.184	0.011	1.000			
0SU	0.002	0.002	0.006	0.623	0.126	0.183	1.000		
1SU	0.000	0.000	0.000	0.106	0.004	0.428	0.246	1.000	
2SU	0.000	0.000	0.001	0.655	0.021	0.335	0.487	0.582	1.000
biochar	0.001	0.001	0.000	0.002	0.001	0.023	0.015	0.001	0.009

BD	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.603	1.000							
2SA	0.089	0.090	1.000						
0UH	0.000	0.000	0.000	1.000					
1UH	0.000	0.000	0.000	0.002	1.000				
2UH	0.000	0.000	0.000	0.275	0.000	1.000			
0SU	0.000	0.000	0.000	0.026	0.929	0.008	1.000		
1SU	0.000	0.000	0.000	0.008	0.501	0.002	0.933	1.000	
2SU	0.000	0.000	0.000	0.064	0.992	0.025	0.975	0.930	1.000
biochar	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

h=50	0SA	1SA	2SA	0UH	1UH	2UH	0SU	1SU	2SU
0SA	1.000								
1SA	0.763	1.000							
2SA	0.050	0.098	1.000						
0UH	0.046	0.092	0.876	1.000					
1UH	0.054	0.090	0.289	0.231	1.000				
2UH	0.015	0.027	0.051	0.054	0.013	1.000			
0SU	0.073	0.121	0.711	0.621	0.570	0.048	1.000		
1SU	0.017	0.044	0.050	0.055	0.013	0.174	0.064	1.000	
2SU	0.018	0.050	0.050	0.054	0.014	0.122	0.076	0.415	1.000
biochar	0.124	0.215	0.078	0.075	0.035	0.779	0.126	0.188	0.008

h=100	0SA	1SA	2SA	0UH	1UH	2UH	0SU	1SU	2SU
0SA	1.000								
1SA	0.163	1.000							
2SA	0.002	0.041	1.000						
0UH	0.000	0.000	0.000	1.000					
1UH	0.000	0.000	0.000	0.461	1.000				
2UH	0.000	0.000	0.000	0.017	0.005	1.000			
0SU	0.000	0.000	0.000	0.681	0.321	0.026	1.000		
1SU	0.000	0.000	0.000	0.037	0.017	0.067	0.120	1.000	
2SU	0.000	0.000	0.000	0.015	0.010	0.059	0.085	0.976	1.000
biochar	0.000	0.005	0.000	0.097	0.074	0.371	0.252	0.667	0.400

h=336.1	0SA	1SA	2SA	0UH	1UH	2UH	0SU	1SU	2SU
0SA	1.000								
1SA	0.473	1.000							
2SA	0.195	0.053	1.000						
0UH	0.001	0.000	0.000	1.000					
1UH	0.000	0.000	0.000	0.744	1.000				
2UH	0.001	0.000	0.000	0.001	0.000	1.000			
0SU	0.001	0.000	0.000	0.442	0.329	0.001	1.000		
1SU	0.000	0.000	0.000	0.046	0.042	0.002	0.175	1.000	
2SU	0.002	0.000	0.000	0.066	0.038	0.015	0.140	0.443	1.000
biochar	0.000	0.006	0.001	0.385	0.386	0.035	0.761	0.458	0.480

h=501.2	0SA	1SA	2SA	0UH	1UH	2UH	0SU	1SU	2SU
0SA	1.000								
1SA	0.480	1.000							
2SA	0.279	0.067	1.000						
0UH	0.001	0.000	0.000	1.000					
1UH	0.000	0.000	0.000	0.912	1.000				
2UH	0.000	0.000	0.000	0.000	0.000	1.000			
0SU	0.001	0.000	0.000	0.370	0.334	0.000	1.000		
1SU	0.000	0.000	0.000	0.097	0.121	0.000	0.533	1.000	
2SU	0.002	0.000	0.000	0.115	0.077	0.008	0.257	0.322	1.000
biochar	0.000	0.009	0.001	0.083	0.076	0.001	0.062	0.001	0.106

Appendix G. T-test for comparison of times needed to reach chosen field capacities (for given pressure heads h).

h=50	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.583	1.000							
2SA	0.124	0.683	1.000						
0UH	0.017	0.342	0.179	1.000					
1UH	0.003	0.127	0.031	0.062	1.000				
2UH	0.011	0.237	0.076	0.069	0.472	1.000			
0SU	0.032	0.369	0.282	0.938	0.161	0.336	1.000		
1SU	0.030	0.400	0.314	0.630	0.075	0.155	0.815	1.000	
2SU	0.027	0.409	0.314	0.408	0.044	0.076	0.727	0.909	1.000
biochar	0.151	0.316	0.052	0.001	0.002	0.004	0.024	0.014	0.007

h=100	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.353	1.000							
2SA	0.186	0.758	1.000						
0UH	0.000	0.002	0.002	1.000					
1UH	0.000	0.000	0.000	0.053	1.000				
2UH	0.000	0.002	0.002	0.148	0.439	1.000			
0SU	0.000	0.003	0.002	0.802	0.227	0.535	1.000		
1SU	0.000	0.003	0.003	0.583	0.059	0.175	0.606	1.000	
2SU	0.000	0.003	0.003	0.298	0.033	0.093	0.513	0.900	1.000
biochar	0.014	0.185	0.195	0.000	0.002	0.007	0.023	0.012	0.005

h=336.1	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.607	1.000							
2SA	0.607	0.991	1.000						
0UH	0.000	0.003	0.002	1.000					
1UH	0.000	0.000	0.000	0.066	1.000				
2UH	0.004	0.003	0.003	0.686	0.423	1.000			
0SU	0.002	0.003	0.003	0.753	0.254	0.886	1.000		
1SU	0.001	0.003	0.003	0.527	0.065	0.517	0.533	1.000	
2SU	0.000	0.003	0.003	0.065	0.026	0.407	0.375	0.818	1.000
biochar	NA	0.181	0.176	0.000	0.002	0.033	0.019	0.011	0.002

h=500.2	**0SA**	**1SA**	**2SA**	**0UH**	**1UH**	**2UH**	**0SU**	**1SU**	**2SU**
0SA	1.000								
1SA	0.633	1.000							
2SA	0.605	0.991	1.000						
0UH	0.000	0.003	0.002	1.000					
1UH	0.000	0.001	0.000	0.074	1.000				
2UH	0.006	0.004	0.003	0.849	0.403	1.000			
0SU	0.003	0.003	0.003	0.765	0.270	0.999	1.000		
1SU	0.001	0.003	0.003	0.410	0.058	0.606	0.472	1.000	
2SU	0.000	0.003	0.003	0.047	0.026	0.534	0.350	0.877	1.000
biochar	NA	0.244	0.223	0.000	0.001	0.034	0.014	0.008	0.001