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A comparison of different methods to determine the Atterberg´s limits in the laboratory

Diploma Thesis

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Declaration

I hereby declare that I have done this thesis entitled “**A comparison of different methods to determine the Atterberg´s limits in the laboratory”** independently, all texts in this thesis are originals, and all the sources have been quoted and acknowledged by means of complete references and according to Citation rules of the FTA.

In Prague, 24.07.2020.

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Ajla Šoše

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I dedicate this master thesis, as crown of my education, to my parents and my brother. Their love, support, inspiration and motivation have been pillars of my life and everything I am today, I am because of them.

Summary

As the water content in the soil increases, the consistency of fine-grained soil changes from solid to plastic state, and eventually to a liquid form. Plastic limit (PL) is the point at which the consistency of the soil is changed from solid to plastic state. Liquid limit (LL) is the point at which the consistency is transformed from plastic to liquid state. These two limits are collectively referred to as Atterberg's (consistency) limits, which are of crucial importance for soil classification and engineering purposes. The aim of this thesis was to examine and compare different methods to determine Atterberg's limits in laboratory. Plastic limit has been determined by rolling thread method, while two basic methods were used for the evaluation of the liquid limits – Casagrande apparatus and cone penetrometer. Disturbed soil samples have been taken from three different localities in Prague: Ruzyně, Suchdol and Uhříněves. All soil samples had the same soil texture – silt loam. For plastic limit test determination, 30 samples have been used; 10 samples for each locality. Twenty-four samples have been obtained per each locality and per each method of liquid limit tests. In total, there have been 144 samples; 72 samples for the Casagrande apparatus and 72 samples for the cone penetrometer. LL values ranged between 31 and 40.2% for Casagrande apparatus, while values were a bit higher for cone penetrometer, varying between 32.2 and 43%. Presented results of laboratory tests show that there was no significant difference in results between Casagrande cup and cone penetrometer. Nonetheless, Casagrande apparatus showed slightly more reliable results, compared to the cone penetrometer, as the first method had lower standard deviation and coefficient of variation values. Precisely, coefficient of variation for Casagrande apparatus varied from 0.4 to 2%, while CV values for cone penetrometer were slightly higher – ranging between 0.5 and 2.3%. Obtained results indicate the need for further research in this area, focusing on acquiring more samples with different soil textures and clay content, preferably from different localities in the Czech Republic.

Key words: Atterberg's limit, plasticity limit, liquid limit, cone penetrometer, Casagrande apparatus

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List of the abbreviations used in the thesis

CEC – cation exchange capacity

CV – coefficient of variation

EC – electrical conductivity

LL – liquid limit

MDM – mud machine method

PL – plastic limit

PI – plasticity index

USCS – unified soil classification system

1. Introduction

One of the most important properties of the fine-grained soils is its consistency. It is determined by the water content present in the soil, which influences the texture, density and firmness of the soil, directly affecting its strength. One century ago, in 1911, Albert Atterberg proposed consistency limits, today widely known after their founder – Atterberg's limits. Even though the original consistency limits contained more limits, after their standardization in 1932 by Arthur Casagrande, three are used: liquid limit (LL), plastic limit (PL) and to lower extent, shrinkage limit (SL). Liquid limit is defined as water content at which soil becomes sufficiently weak and flows as a liquid. The plastic limit is the water content at which soil is sufficiently hard and rigid so that it becomes brittle and can fracture easily. Atterberg proposed consistency limits primarily for agriculture, because he was studying influence of consistency of soil on tillage. He proposed plastic limit as the highest possible soil water content for cultivation (Deng et al., 2017). Later on, Casagrande and Terzaghi have implemented these consistency limits as principal work for soil mechanics, we observe many other uses of this soil feature. For example, Atterberg's limits are used for soil classification purposes, especially as preliminary tests for analysis of soil for potential construction objectives. Furthermore, they are used to characterize and analyze other soil properties, such as permeability, toughness, swelling, shrinkage, strength and compressibility.

There are two methods to determine liquid limits of soil – Casagrande cup (percussion method) and fall cone penetrometer. Both are used still today and widely accepted, but by different countries. For example, Casagrande apparatus is widely accepted in the USA, while European countries prefer fall cone penetrometer technique. However, Casagrande method is considered to have more limitations, compared to cone penetrometer, such as: stiffness of base rubber (i), base dimensions (ii), insulation from the supporting table (iii), dimensions and weight of the cup (iv), drop height (v), frequency of drops (vi), soil type (vii), wear of the grooving tool (viii), tendency of the soil halves to slide together (ix), operator judgment and experience with handling the tool (x) and maintenance issues (xi) (Kayabali et al., 2016). In order to overcome these restrictions, fall cone penetrometer was developed, which is simpler, easier to operate, offers higher degree of reproducibility and depends less on operator's judgment. Unfortunately, both instruments do not yield same results for different types of soils, and many, sometimes significant errors can be found in various publications by different authors. Such discrepancies in results make it very difficult to draw unified conclusions, which can be accepted on all soil types worldwide. However, in spite of all Casagrande cup method's limitations, soil classification systems require tests performed by Casagrande method in European countries.

2. Scientific hypothesis and objectives of work

The Atterberg's limits are used for classification, characterization and even prediction of soil behavior for geotechnical and engineering purposes. Hence, liquid and plasticity limits are the most important soil physical properties with respect to many landscape constructions, such as dams of water reservoirs, pond constructions, flood protections etc. Atterberg's limits are thus essential tests in geotechnical and soil sciences worldwide.

The aim of this thesis is to compare and contrast different laboratory methods for liquid limit (LL) determination. The focus will be on analysis and correlation between two widely used instruments for liquid limit measurement: cone penetrometer and Casagrande cup. It is important to assess which of the two techniques is more suitable for different levels of education and expertise of operator, which method yields better, more clear and repeatable results, which one is easier, faster and less sensitive. These parameters are important to be tested in order to create less discrepancy in results and obtain more reliable results in shorter time frame, so that results can be drawn more easily.

This research was framed by three most important questions:

- Will the two standardized methods for the Atterberg's limits determination give very similar and comparable results?
- Which instrument will be more efficient for LL determination in laboratory, in terms of yielding results with more consistency and repeatability?
- Which instrument will have less variability in errors in results, considering that samples from different localities will be taken?

Taking into consideration current literature and experience of authors who have experience working with the Atterberg's limits, the hypothesis that the standardized methods for the Atterberg's limits determination will give very similar, statistically proven and comparable results. To answer the proposed research questions and test the present hypothesis, this thesis will be firstly outlined and compared by literature and findings by other authors. It will be followed by the analysis of the soil samples collected at the three different locations in Prague, Czech Republic and completed with interpretation of results and suggestions for future research.

3. Literature Overview

Soil is considered as the fine earth which covers land surfaces as a result of weathering of rock materials or the accumulation of mineral matter transported by water, wind or ice. Soil plays a vital role in sustaining life on Earth. Nearly all food which humans consume, except for the food gathered from the marine environments, is grown on Earth's soils. This agricultural productivity is one of the most important functions of soil. It provides paper and clothing, basic materials used in many different industries, and is foundations for roads and buildings. Besides these, soil provides medium for pollutants, water, nutrients and habitat for microorganisms, plants, animals and humans. It is a system in which biological, chemical and physical interactions take place. Additionally, it provides the environment for breakdown and immobilization of substances added on its surface, such as fertilizers, pesticides and different waste products. Soil is able to buffer, filter, degrade, detoxify and immobilize organic and inorganic substances, harmful or beneficial (Nortcliff et al., 2006).

There are many definitions of soil. For example, the Natural Resource Conservation Service (NRCS) defines soil as "a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterized by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment". On the other hand, the Soil Science Society of America (SSSA) defines soil in terms of its genetic and environmental factors, as "unconsolidated mineral or organic matter on the surface of the Earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product – soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics". This means that definitions of soil depend on function it provides (Schoonover and Crim, 2015). Even though it is such critical component of nearly every ecosystem on our planet, it is often taken for granted and destroyed instead.

Water has the most effect on biological, chemical and physical properties of soil. It affects microbial life, providing either aerobic or anaerobic conditions, hence reduction or oxidation environment for soils. Furthermore, water influences the appearance of hydro morphism, which is permanent or temporary state of water saturation in soil, associated with reduction conditions. When there is no oxygen available in soil, all soil pores are filled with water, which results in production of very heavy soil, which are very difficult to process for agricultural or engineering purposes. Water influences appearance of accumulation or depletion features in soil, visible in iron and manganese nodules and coatings, which increase with increase of humidity of soil. In the end, water has power to shape the soil particles and is determining factor to classify soil particle types. To summarize, water influences different color of the soil (from dark brown, to red, green, yellow and even blue), different saturation levels (connected with rainfall or snowmelt, as well as humidity levels in soil), appearance of manganese or iron coatings in the soil, as well as bleaching phenomenon, prevailing conditions in the soil (either reduction or oxidation), and soil structure, both in terms of classes of soil structure (which can vary from very fine, fine, medium, coarse and very coarse) and types of soil structure (which can vary from granular, blocky, columnar, platy or structureless structures).

Soil behavior depends on different factors: geography and climate, mineral composition, soil structure and water content. It is even possible to say that water content is essential element for soil behavior prediction. Consistency, an important physical property of soil, is term used to describe stiffness of soil and is a property which depends on amount of water present in the soil. Such water content levels at which soil is transformed from one state or another are called consistency limits and are important in determination of physical and engineering characteristics of soil, especially aggregation of particles. Consistency limits depend on many different factors, but most important ones include type and amount of clay, exchangeable cations and water chemistry (Aksoy et al., 2010). Soil water content influences change of soil volume, through process of shrinkage or swelling. Soil volume increases during wetting and it decreases during drying. Expansion is one of the most important geotechnical problems in soils, and shrinkage influences agriculture and engineering properties of soils (Rezaee et al., 2019).

If soil is repeatedly and continuously mixed with water, it is becoming more and more soft, until it loses its plasticity and is transformed into viscous fluid. In order to describe these transitions, in 1911, Swedish scientist Albert Atterberg identified soil's consistency limits, which are today known as Atterberg's limits. These limits are actually water contents in soil connected with critical stages of soil's strength, as depicted in Figure 2 (Niazi et al., 2019). They are of key characteristics in soil mechanics because they determine interaction between the solid and the liquid phases in the soils, and thus provide the possibility of classifying soils into groups with similar mechanical properties (Dolinar et al., 2012). Hence, Atterberg's limits are used in classification, characterization and even prediction of soil behavior for geotechnical and engineering purposes (Polidori, 2007). Deformability, expansion, hydraulic conductivity and strength of soil are some of the characteristics which can be predicted with help of Atterberg's limits (Dolinar et al., 2007). However, it is important to note that strength of soils is highly affected by humidity and moisture conditions which are found in soils. This is especially related to clayey soils (Bláhová et al., 2013), as they have the capability to hold high amounts of water and drain slowly. Water content is different between different states of soil, and specific water content can describe the boundary of each state of soil, as well as properties of soil. Initially, Atterberg introduced five limits: the upper limit of fluidity, the lower limit of fluidity – flow limit (today's liquid limit), the sticky limit, the roll-out limit (today's plastic limit) and cohesion limit. Today, we identify four consistency limits (between liquid, plastic, semi-solid and solid state, see Figure 1). Out of these four consistency limits, we recognize two main Atterberg's limits: liquid limit (LL) and plastic limit (PL). The difference between the two is called plasticity index (PI). Liquid limit of soil is defined as water content when soil changes from liquid to plastic, while plastic limit is characterized as water content at which soil changes from being ductile to brittle. Another difference between these two limits is speed of these transitions; transition for liquid limit is gradual, while transition for plastic limit is sudden (Mousavi et al, 2019). Plasticity index is used in assessment of soil's capacity to hold and retain water. Clays which are able to swell (such as montmorillonite, smectite, bentonite, chlorite, etc.) have high PI (Spagnoli et al., 2019). PI is used for soil classification purposes, especially as preliminary tests for analysis of soil for potential construction purposes. Furthermore, they are used to characterize and analyze other soil properties, such as permeability, toughness, swelling, shrinkage and compressibility (Abbas, 2018; Aksoy et al., 2010). Atterberg's limits can be correlated with clay mineralogy to understand, correlate and evaluate the soil and mechanical characteristics before the constructions. This is very important in clayey soils, because due to their low permeability, mechanical tests, such as oedometer or compression tests, can take a lot of time, up to some months or even years. This is not very useful for initial construction evaluation, as such tests are extremely time consuming (Schmitz et al., 2004). These scientists have concluded that quick assessment of clay can be made for the engineering properties, if mineralogic composition of clay is known or available.

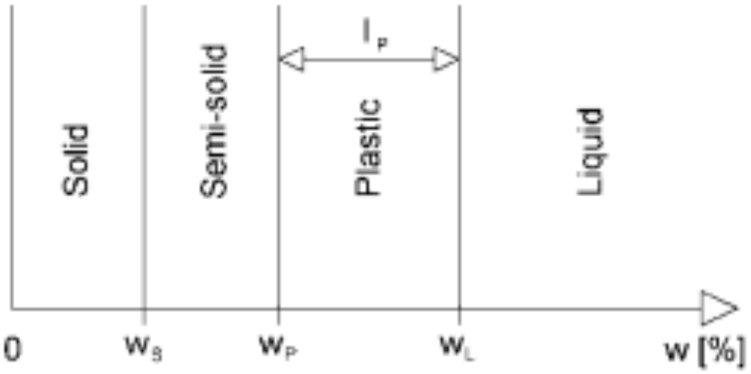


Figure 1: Consistency (Atterberg's) limits.

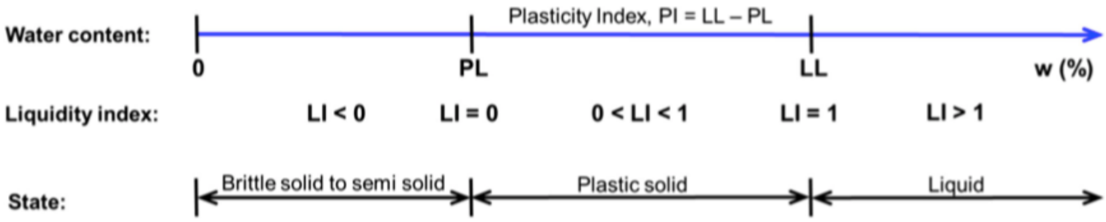


Figure 2: Relationship between water content, consistency limits and soil state (Niazi et al., 2019).

In the plastic range, soil mechanical behavior is plastic and irreversible without cracking upon load. In the semi-solid state, which is a state between shrinkage limit and plastic limit, soil is fragile and behaves in a brittle manner (Zolfaghari et al., 2015). Plastic limit is often used as arbitrary threshold for workability of soils, as it is considered as water content at which soils can be worked with, without causing structural damage. For this reason, consistency limits are suitable for field assessment, but not applied to non-cohesive soils which are either non-plastic or highly compacted. In this way, consistency limits can be used for assessment and calculation of soil's capability for trafficability and workability with machinery tools (Müller et al., 2011).

Atterberg's limits depend on many factors, which include soil composition (content and type of clay minerals, organic matter), pH, temperature, cation exchange capacity, type and content of cations in soil solution. Among these properties, mineralogical characteristics are the most important ones for Atterberg's limits determination. Even though many scientists have compared relationships between Atterberg's limits and mineralogy, exact conclusions cannot be drawn, because results cannot be valid and applicable for all soils. The reason for this lies in the fact that cohesive soils contain both clay and non-clay minerals. However, interactions between clay minerals and water content have major effect on water-holding capacity of soils, so Atterberg's limits vary between expandable (which have both external and internal surfaces, such as montmorillonite) and non-expandable minerals (which have only external surfaces, such as kaolinite and illite). Paper by Dolinar et al (2007) summarized relationships between clay mineralogy and Atterberg's limits, stating that:

1) The hydraulic conductivities of different clays have approximately equal values at liquid limit, implying that pore sizes are approximately equal size for all clays.
2) The water content is directly proportional to soil surface area and matrix suction, implying that ratio of absorbed water to clay surface area should be of approximate value at the liquid limit.
3) There is linear relationship between liquid limit value and clay content, implying that most of water in soils is associated with clay at the liquid limit.

This paper has identified that in soils without expandable clays, plastic and liquid limits were mostly related to their surface area and clay content. However, because plastic and liquid limits in soils with expandable clays depend on interlayer water content, these expandable clay mineral contents are needed in order to calculate PL and LL values.

Article by Zolfaghari et al. (2015) argues that land use and slope position can indirectly affect soil consistency limits and plasticity indices. This could be achieved through changing physical and chemical properties of soil, which could regulate soil consistency. They point out that influence of land use changes and management practices affect properties such as: soil hydraulic properties (i), soil strength (ii), sorption capacity (iii), aggregate tensile strength (iv), degree of compactness (v) and soil aggregation (vi). For example, the studies they analyzed conclude that systems without any tillage had lowest values of soil particle density, but highest values of LL, PL, PI and OM (organic matter). Additionally, their study showed that irrigated farms increased OM, LL, PL and PI, probably because of high biomass production and addition of plant residues to the soil in irrigated farms.

However, many anthropogenic influences on consistency of soils should not be neglected. For example, acid rains and usage of different chemicals for agricultural purposes influence both physical and chemical properties of soil and have influence on Atterberg’s limits as well (Polidori, 2007). This is why Atterberg’s limits, influenced by all above-mentioned factors, provide insight in soil consistency characteristics and can be used to predict its behavior and are vital tests in almost all soil-related experiments.

3.1. History of Atterberg’s limits

As mentioned earlier, Albert Mauritz Atterberg, a Swedish agricultural scientist and chemist, has discovered and described Atterberg’s limits. His interest was mainly in soil classification and plasticity of soil. He was the one who determined that plasticity is an important characteristic of clay, which was considered as the most complex and unpredictable soil type. His work for soil classification was recognized formally and internationally by the International Society of Soil Science in 1913, three years before he passed away. Nonetheless, his work served as inspiration to many other scientists, some of which achieved significant advances in soil sciences, which are extremely relevant and important even today.

Arthur Casagrande is an important person in soil sciences, as his work left an important imprint for the future generations. He was born in 1902 in Austria, where he graduated in civil engineering. After World War I, jobs in construction were limited, and because he was the main provider for his family, he moved to the United States. There, he applied for a job at the Massachusetts Institute of Technology (MIT), where he met Karl Terzaghi, a civil engineer and geologist. Karl von Terzaghi was born in 1883 in Prague, Czech Republic and later moved to Austria. He studied mechanical engineering and spent large part of his career in research as well, in Austria, United States and Turkey. He was pioneer in soil mechanics and geotechnical engineer, widely known as “Father of Soil Mechanics”, as he described theories of consolidation, bearing capacity and stability, contributing enormously to the civil engineering sciences, mostly soil mechanics. He has also stated Terzaghi Principle, which says that “total stress is equal to the sum of effective stress and pore water pressure”. As mentioned earlier, Terzaghi met Casagrande on MIT, when Casagrande was hired as Terzaghi’s private assistant, which gave them many opportunities to work together. They were most concerned with researches on improving soil testing apparatuses and procedures. Casagrande moved to Austria for a couple of years, where, together with Terzaghi, designed and developed soil mechanics laboratory and equipment, as visible on Figure 3, left (Aires et al., 2018).

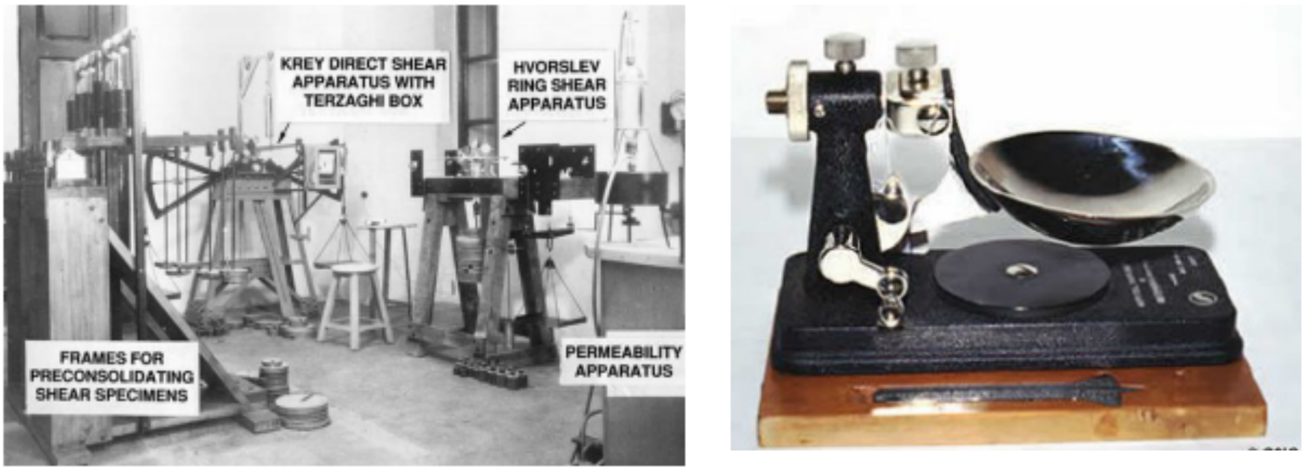


Figure 3: Soil mechanics laboratory with equipment installed by Arthur Casagrande and Karl von Terzaghi at the University of Vienna (left). Casagrande cup, model from 1942, design by Arthur Casagrande (right). Taken from Aires et al., 2018.

Atterberg has great influence on both sciences, and his impact resulted in many breakthroughs they have achieved through their work. Terzaghi introduced Atterberg's limits into modern soil mechanics and Casagrande created and standardized testing device for Atterberg's limits – Casagrande cup, as visible on Figure 3, right. These two achievements contributed in making Atterberg's limits fundamental tests in geotechnical and soil sciences worldwide (Li et al., 2019).

Nowadays, Atterberg's limits are essential, key factors for identification and classification of soils in the Unified Soil Classification System (USCS). As they are related to the amount of water, they allow description of different soil consistency states due to the water content present in soil. Conventionally, Atterberg's limits and especially their plasticity indices, are used to indicate plastic behavior of soil (Mousavi et al, 2019).

Atterberg's limits were first proposed in 1911 to establish range of water content in plastic phase of soils, for agricultural purposes. With more frequent applications, when they were used to describe soil behavior at different water contents, Atterberg's limits started playing vital roles in industrial, geotechnical and soil engineering studies (Mousavi et al, 2019).

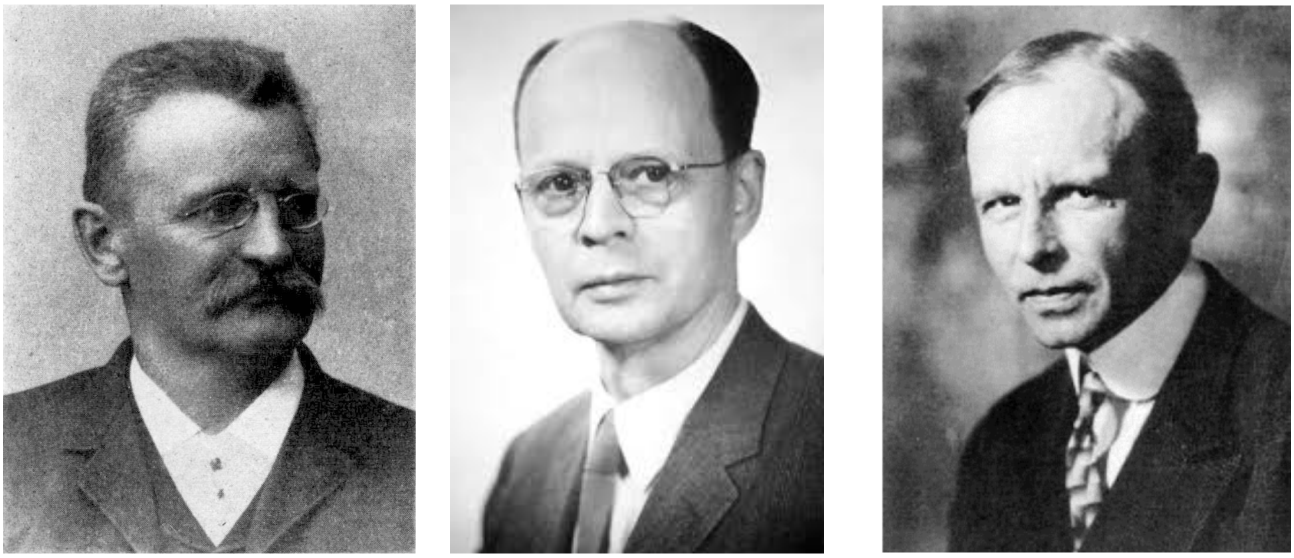


Figure 4:Three most important scientists for Atterberg’s limits: Albert Atterberg (left), Arthur Casagrande (middle) and Karl von Terzaghi (right).

3.2. Applications of Atterberg’s limits

As previously mentioned, most prominent usage of consistency limits is observed for soil classification, as well as for construction purposes. Below, summary of these two, most important applications can be found. Soil classification will be discussed first, as it is preliminary test to be done before any construction takes place.

3.2.1. Soil classification

Classification of soil is used to arrange soil into groups and subgroups in order to describe its characteristics. This step is essential before designing and constructing any project, because engineering characteristics of soil (such as permeability, strength and rigidity) are influenced by soil’s properties (such as soil particle shape, size, arrangement and structure). There are many soil classification systems, mostly relying on the same classification principles, including distribution of particles and plasticity (Al-Mamoori et al., 2020). However, the two main systems include USCS (Unified Soil Classification System) and AASHTO (American Association of State Highway and Transportation Officials) System. USCS was developed by Casagrande in 1948, while AASHTO was developed by Terzaghi in 1929. Both classification systems were revised several times. USDA (United States Department of Agriculture) soil taxonomy is another way for classification of soil types according to their parameters.

As mentioned, one of the basic parameters for soil classification is soil particle size. The USDA classification is one of the most commonly used systems in agriculture and is based on particle size distribution within the soil texture triangle (see Figure 5). The USCS model (see Table 1) also uses soil particle size distribution for classification, as well as Atterberg's limits and plasticity indices to define silt and clay particles. However, for some soils and some studies, these two classification systems cannot be correlated, which is why laboratory tests need to be conducted to achieve complete accuracy. This is why many studies focus mainly on the USCS in order to model, predict and define soil groups. It provides more information about soil properties, such as organic matter, drainage, bulk density, available water capacity and other characteristics, which makes it easier for scientists to model predictions of USCS soil groups using particle size distribution (Heštera, 2020).

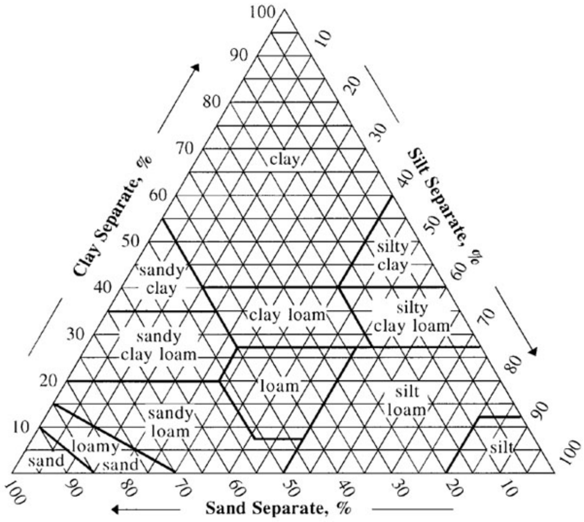


Figure 5: USDA (United States Department of Agriculture) soil classification, based on soil texture triangle – clay, silt and sand fractions of soil.

Table 1: USCS (Unified Soil Classification System) classification, based on fine-grained soils (clays and silts) and coarse-grained soils (sands and gravels).

Major Division	**USCS Group Symbol**	**Typical Description**
Fine Grained Soils Clays and silts >50% (by weight) passing the 75µm (#200) sieve	***CH***	*High plasticity clay*
	CL	*Low plasticity clay*
	MH	*High plasticity silt*
	ML	*Low plasticity silt*
Coarse Grained Soils Sands and gravels May contain up to 49% silt and clay	***SC***	*Clayey sands*
	SM	*Silty sands*
	SW	*Clean sand – well graded*
	SP	*Clean sand – poorly graded*
	GC	*Clayey gravel, sand-clay-gravel*
>50% (by weight) coarser than 75µm (#200) sieve	***GM***	*Silty gravel, gravel-sand-silt*
	GW	*Clean gravel- well graded*
	GP	*Clean gravel- Poorly graded*

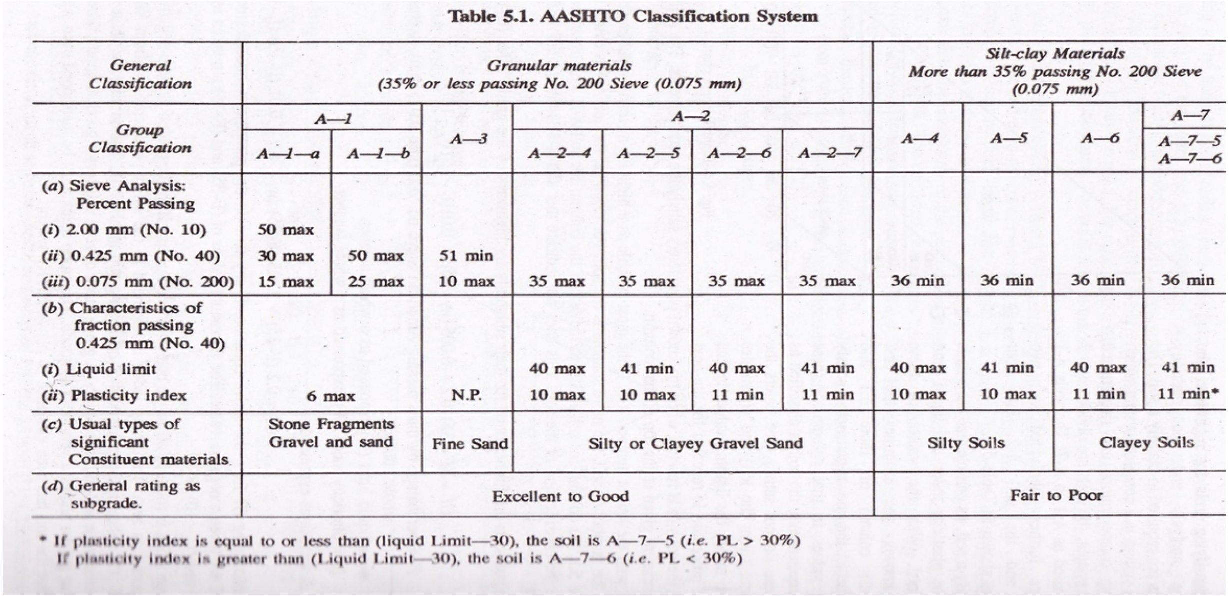


Table 5.1. AASHTO Classification System

General Classification	*Granular materials (35% or less passing No. 200 Sieve (0.075 mm)*							*Silt-clay Materials More than 35% passing No. 200 Sieve (0.075 mm)*			
Group Classification	*A—1*		*A—3*	*A—2*				*A—4*	*A—5*	*A—6*	*A—7*
	A—1—a	*A—1—b*		*A—2—4*	*A—2—5*	*A—2—6*	*A—2—7*				*A—7—5* *A—7—6*
(*a*) Sieve Analysis: Percent Passing											
(*i*) 2.00 mm (No. 10)	50 max										
(*ii*) 0.425 mm (No. 40)	30 max	50 max	51 min								
(*iii*) 0.075 mm (No. 200)	15 max	25 max	10 max	35 max	35 max	35 max	35 max	36 min	36 min	36 min	36 min
(*b*) Characteristics of fraction passing 0.425 mm (No. 40)											
(*i*) Liquid limit				40 max	41 min	40 max	41 min	40 max	41 min	40 max	41 min
(*ii*) Plasticity index	6 max		N.P.	10 max	10 max	11 min	11 min	10 max	10 max	11 min	11 min*
(*c*) Usual types of significant Constituent materials	Stone Fragments Gravel and sand		Fine Sand	Silty or Clayey Gravel Sand				Silty Soils		Clayey Soils	
(*d*) General rating as subgrade.	Excellent to Good							Fair to Poor			

* If plasticity index is equal to or less than (liquid Limit—30), the soil is A—7—5 (*i.e.* PL > 30%)
If plasticity index is greater than (Liquid Limit—30), the soil is A—7—6 (*i.e.* PL < 30%)

Figure 6: AASHTO (American Association of State Highway and Transportation Officials) classification, based on sieve analysis, classifying soils in groups from A1 to A7.

Generally, all soils are classified into fine-grained or coarse-grained soils, depending on distributions of particles of the same size. They can be determined based on their passage or retention on sieve with specific diameter (see Figure 7). Fine-grained soils are the soils which can pass through 0.075 mm sieve, while coarse-grained soils are soils which are retained on 0.075 mm sieve. Fine-grained soils are furthermore classified into clay or silt using a hydrometer test, while coarse-grained soils such as sand, gravel, cobbles and boulders are just retained on the sieve. Soils can be additionally subclassified based on their consistency properties (Al-Mamoori, et al., 2020). There are three main fractions of soil particles: clay, silty and sandy soils. Soil texture is classified according to the Soil Taxonomy (Soil Survey Staff, 2014) in this thesis.

Clay particles are which have particles smaller than 0.002 mm. They are wet, sticky and cold in the winter, while baked dry and smooth in the summer. Clay soils have the capacity to hold high amounts of water and drain slowly. They have the smallest particles, which is why they tend to settle together, so that little amount of air passes through their pores. They are heavy soils and rich in nutrients, because they drain water slowly and are able to retain all plant nutrients. However, these soils are very difficult to work on when they are too dry or too wet (sticky).

Silt particles are between 0.002 and 0.05 mm. Those are particles with intermediate sizes between clay and sand, whose mineral origin is feldspar and quartz. Silt can occur as soil, often mixed with soil or clay, or as sediment, usually mixed with water. Silty soils have floury feel when dry, and slippery feel when wet. They can retain water longer than sandy soils but cannot hold much nutrients even though they are fairly fertile. Due to their moisture-retentive characteristic, silty soil is cold and drains water poorly. Silt particles can be easily compacted and are prone to being washed away by rain.

Sand particles range between 0.05- and 2-mm. Sand-rich soils have largest particles among soil types. Because of large spaces between particles, these soils cannot hold water, which is why plants do not have chance of using nutrients in this type of soils. Sandy soils are light, warm and dry and tend to be acidic. In contrast to clayey soils, they are much easier to work on, even though they are low in nutrients.

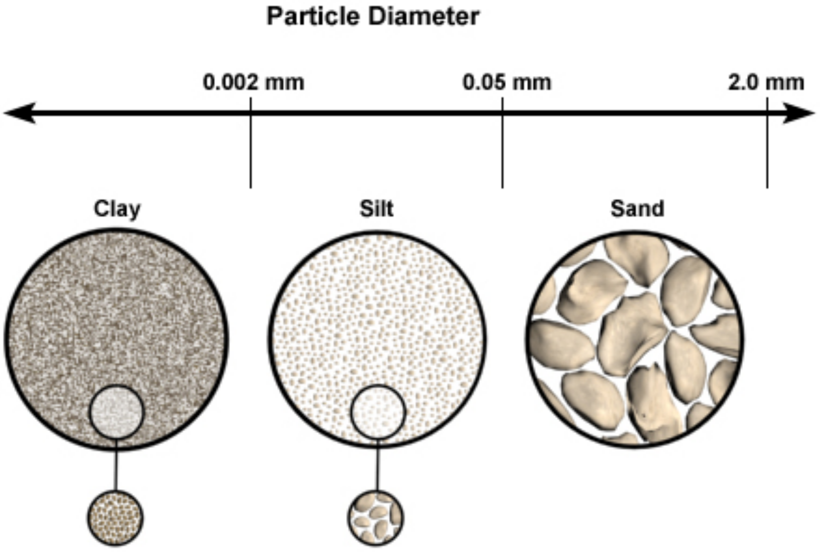


Figure 7: Comparison between main three soil types: clay, silt and sand.

3.2.2. Construction purposes

All geotechnical structures require deep study and understanding about soil physical properties before starting with structural design (Al-Adhadh et al., 2019). Atterberg's limits provide information for interpretation of mechanical and physical properties of soil, such as shear strength, compressibility, shrinkage and swelling potential. These consistency limits are extremely important for construction purposes which have infrastructure applications, such as buildings and road constructions (Zolfaghari et al., 2015). More recently, Atterberg's limits have been proposed as indicators for soil vulnerability to degradation processes of both natural and anthropogenic origin. For example, soils which have limited cohesion, when subjected to water saturation, are very susceptible to erosion. In this way, consistency limits can serve as indicators for soil vulnerability to erosion. As the Atterberg's limits refer to the highest and lowest content of water in the soil, they become extremely important for prediction of influence of surface runoff and rainfall (Deng et al., 2017). Erosion is extremely big problem for some parts of the world and is an important determinant for decision on whether or not to start with construction works. Through processes of erosion, landslides are formed, and soil becomes degraded. Such flooding and debris flow can pose as hazard for sustainable development, agriculture and engineering in nearby regions.

3.3. Liquid limit

Liquid limit (LL) is the point at which soil changes from plastic to liquid and is measured as a percentage. As water content in soil increases and it approaches to liquid limit, space between particles increases and interactions between soil particles decrease. This is why mechanical properties change, disrupting densely packed soil particles arrangement and converting it to loosely packed liquid (Spagnoli, 2012). Liquid limit is most common test for classification of fine-grained soils in geotechnical engineering (Özer, 2009). Being the maximum value of water content in a soil, LL can vary over a wide range. This is why it is used in preliminary analyses and soil classifications. It has been concluded by Shumobe et al. (2019) that shear resistance of soils at their LL has a range between 0.4 and 6 kPa. Its wrong determination can lead to rejection of suitable materials, or acceptance of inappropriate ones. In the end, additional treatments would be needed d to eliminate the mistake (Crevelin et al., 2019). These would be both time-consuming and costly.

Two most widely used methods for calculation of liquid limit include Casagrande cup and cone penetrometer technique. They both have advantages and disadvantages over each other, and many authors have spent years comparing them. Additionally, they are not used equally in all locations throughout the world – different countries prefer one technique over the other.

3.3.1. Casagrande cup

Casagrande method (also called percussion method) was first designed by Arthur Casagrande in 1932 and modified in 1949, in order to improve its original method, which had repeatability issues. We consider the latter device as the standard one and a universal technique for conducting various geotechnical tests. It consists of semi-spherical cup made of brass, which can be repeatedly dropped onto a hard rubber base from height of 1 cm (Mishra et al, 2011), at rate of 2 blows per second. The number of blows to the groove is recorded – the number should be larger than 12, but lower than 38. Liquid limit would represent the moisture content at which it took 25 blows to cause the groove to close over distance of approximately 1.3 cm (Rezaee et al, 2019). A detailed procedure is proposed by the Czech state standard ČSN 72 1014 – Laboratory determination of liquid limit of soils (Fojtova et al., 2009). The American Society for Testing and Materials regards Casagrande bowl as standard method for testing liquid limits.

It is standardized by standardized by DIN 18122-1:1997-07 (1997), AASHTO T89-07 (2007) and ASTM D4318-10 (2010) (Spagnoli et al., 2019).

There are differences in design of Casagrande cup; different countries use different materials as a base of the apparatus. In its original design, Casagrande proposed base material of apparatus to be a hard rubber, with four rubber feet (to provide isolation between the apparatus and working surface) placed under the base. In contrast to this construction, United Kingdom uses softer base, with no additional rubber feet, so that the base is placed directly on the working surface (Özer, 2009). Again, such variations can have direct impact on reproducibility of results.

It is recommended that measurement by cone penetrometer is done at least with four trials, in order to get more precise results. Water content obtained after drying the soil is plotted on the graph versus logarithm of blows (Quintela et al., 2014).

3.3.2. Cone penetrometer

In order to overcome constraints of Casagrande cup, another technique, called cone penetrometer, or fall-cone apparatus, was developed. Originally, it was suggested by the Geotechnical Commission of the Swedish State Railway (GCSSR) in the period between 1914 and 1922. Liquid limit in cone penetrometer test is slightly different than the one obtained by Casagrande apparatus. LL is defined as water content which corresponds to cone penetrated to specific depth into the soil sample. It is important to note that the depth of penetration is directly dependent upon weight and angle of cone (Mishra et al., 2011). Standard cones used are 60 g / 60° and 80 g / 30° (Fojtova et al., 2009). Cone penetrometer is standardized by ISO/TS 17892-12:2004 (2004) (Spagnoli et al., 2019). In Czech Republic, the procedure is given in the new European standard ČSN CEN ISO/TS 17892/12: Geotechnical investigation and testing – Laboratory testing of soils – Part 12: Determination of consistency limits (Fojtova et al., 2009). This technique is preferred by European Standard and hence is used in many soil laboratories across Europe (Spagnoli, 2012).

Multipoint approach is advised for this method as well, recommending four tests. Water content should be read at 25 blows or 20 mm penetration in order to assess the liquid limit, as advised by Quintela et al. (2014). In the Czech Republic, cone with angle of 30° and weight of 80 g is placed on a smooth surface of a sample and is allowed to sink into a depth of 20 mm during five seconds by self-weight (Fojtova et al., 2009).

In literature, cone penetrometer is sometimes referred to as Vasiljev cone, named by Russian researcher Piotr Vasiljev. It was proposed in 1942 and first mentioned in Soviet Union Standard GOST 5184 in 1949.

3.3.3. Benefits and limitations of Casagrande apparatus and cone penetrometer

As the oldest technique, Casagrande cup has numerous limitations. The most important ones include difficulty of cutting the ideal groove and slow speed of operation (Spagnoli, 2012). Additionally, the repeatability of the experiment is affected by operator's judgement (Verástegui-Flores et al., 2014). Due to the fact that percussion method is highly operator-dependent, degree of repeatability of experiments conducted by this technique is quite poor (Di Matteo, 2012). Niazi et al (2019). include further limitations such as stiffness of the base, insulation from supporting platform, physical properties of cup, drop frequency, wear of the grooving tool, difficulty of cutting the groove in certain soil types, operator judgment, sensitivity to operator in adjustment of apparatus, maintenance problems and less reproducible results. Article by Hrubesova et al. (2016) also mentions that cone penetrometer method is easier, faster and less sensitive, which allows better reproducibility of experiment, which is why it is more widely accepted by many European researchers. Besides Europe, fall-cone apparatus is also widely accepted in India, Canada, Japan, Russia and China, while Australia accepts both methods as equally relevant (Di Matteo et al., 2015). In spite of all disadvantages of Casagrande cup and its widest acceptance mostly in the USA, soil classification systems require tests performed by Casagrande method in European countries (Di Matteo, 2012).

Despite general superiority of cone penetrometer over Casagrande cup, it is important that it also has some limitations. For example, it can be sensitive to different manufacturing variations, which can vary even from country to country. Even though Hrubesova et al. (2016) state that cone penetrometer method is faster, Niazi et al. (2019) argue that even despite its simplicity, time consumption for both methods is nearly the same.

It is important to stress that both devices do not work in the same manner with different types of soils and hence do not produce the same results. Additionally, there are discrepancies in results even at this point. For example, according to Li et al. (2019), Casagrande method yields larger variations in liquid limit values (usually due to operator judgement, wear of grooving tool and difference in base materials), which cone penetrometer was able to overcome. Same results were confirmed by Niazi et al. (2019). On the other hand, cone penetrometer will yield higher values of liquid limit for low-plasticity clays, as observed by Di Matteo (2012). However, Niazi et al. (2019) state that liquid limit differs greatly for cone penetrometer for high to very high plasticity soils. Conversely, for more liquid soils (clays with liquid limit higher than 60-70%) (Verástegui-Flores et al., 2014), or for soils with higher plasticity (Mishra et al., 2011), Casagrande technique produces higher values. These discrepancy in liquid limit values are due to clay content in the soil and behavior of clay under different deformation mechanisms created by these two methods (Mishra et al., 2011). As a result of differences in these values, plasticity indices can be quite confusing, and it is difficult to draw conclusions, which leads to significant differences in classification of soils.

Results are not the only important parameter which needs to be considered. Repeatability and reproducibility of an experiment are critical factors as well. They are important because they are quantifiable as well and provide further understanding in variability of test results, based on which potential improvements can be suggested. For example, these characteristics can be used to propose enhancement of testing device or additional training for the operator (Li et al., 2019).

Even though there are different laboratory and field methods available, it has been pointed out that most of them do not account for reproducibility and repeatability. Such errors can arise from faulty testing device, non-experienced operator. Because of these reasons, it is important to constantly work on improving both of these.

More recent studies argue that traditional methods for Atterberg's limit determination are slow, time-consuming and often inaccurate and unreliable (especially when there are many samples to be tested, or unexperienced operator is conducting the experiment). This is why there is increasing need for design of faster and more acceptable method for Atterberg's limits identification. Diffuse reflectance spectroscopy is one of these novel methods, which is a quick and simple method for identification of many different soil properties (Mousavi et al, 2019).

Both methods and instruments have specific advantages and disadvantages over each other (see Table 2). Generally, it can be concluded that Casagrande apparatus has more limitations over fall cone penetrometer.

Table 2: Comparison between Casagrande apparatus and cone penetrometer – advantages and disadvantages.

CASAGRANDE CUP		**FALL CONE PENETROMETER**	
ADVANTAGES	*DISADVANTAGES*	*ADVANTAGES*	*DISADVATAGES*
Widely accepted in the USA	Slow	Simple procedure	Approximately equal time consumption
Required for soil classification systems	Difficult to cut ideal groove	Less operator-dependent	Sensitive to manufacturing variations
	Highly operator-dependent	Better reproducibility	
	Poor repeatability		
	Grooving tool gets worn out		
	Different base materials and cup physical properties		
	Difficulty of cutting groove in certain soils		
	Maintenance problems		

Article by Niazi et al. (2019) analyzed results obtained from 43 different studies, most of which are mentioned in this paper. Analyzed studies have used different cone angles of cone penetrometer, different base materials of Casagrande cups, different soils (in terms of soil type and texture; ranging from natural and manufactured soils, to dredged marine sediments and sedimentary deposits, soils with kaolinitic, bentonitic and illitic clays) and from different geographic regions (ranging from the USA, Europe, Asia, Africa and Latin America). Based on analysis of these studies, they summarized the following conclusions:

1) Cone penetrometer method can reproduce the standard Casagrande cup method with liquid limit with reasonable accuracy (relative error of approximately 10%).
2) Both methods produce slightly different results at different ranges of liquid limit. The LL determined by Casagrande apparatus and cone penetrometer tend to have similar values when LL is in range between 30 and 50%. However, the difference between their values increases when plasticity of soil increases, which means that this difference becomes extremely significant in extremely high plasticity soils.

3.4. Plastic limit

Plastic limit is found at other end of consistency range, limit which separates semi-solid state from plastic state. It is the lowest water content found in soil, when water is so dried it loses its plasticity (Fojtova et al., 2009), Atterberg's first definition of plasticity was that it is the ability of soil to roll out into threads, so plastic limit (PL) can be determined when threads crumble into smaller pieces. Nowadays, the standard BS EN ISO 14688-1:2002 defined plasticity as "the property of a cohesive soil to change its mechanical behavior with change of moisture content" (Barnes, 2013). As LL, plastic limit is also obtained as percentage. However, it is not linked to specific strength value, unlike liquid limit (Shimobe et al., 2019).

Rolling thread method was widely accepted and is still used today in many soil mechanics laboratories. However, it also has some limitations and there have been attempts to perfect the method in order to obtain more reliable and applicable results. Even though there are different tools to test the PL, only rolling thread method is used in this thesis. Besides this one, mud machine method is also discussed and summarized below.

3.4.1. Rolling thread method

The first method to describe soil transition to plasticity was called rolling thread method. The literature states that this procedure was developed by Terzaghi in 1926 and is called Terzaghi's bead rolling method (Kayabali et al, 2016). PL is defined as soil water content at which soil begins to crumble when it is rolled in threads of about 3 mm (see Figure 8). In this technique, soil is rolled in threads on flat and non-porous surface (such as glass). During this experiment, soil gradually loses water, so water content decreases until the thread starts to break apart at larger diameters (Rezaee et a, 2019). It is quite simple but is still widely used as an experimental tool. However, this procedure subjects soil to complex stress, which results in soil crumbling at the end of experiment. Additionally, there are few factors which can affect the results of the test, which include: applied pressure to the soil (i), width of hand contact to soil diameter (ii), friction between soil, hand and base plate (iii), speed of rolling (iv), personal judgment of operator (v) and risk of sample contamination (vi). Study by Sherwood (1970), as summarized by Kayabali (2016), state that the most important factor which affect the results of the test is judgment of operator. This means that this method is non-mechanical and is subjective in nature. Therefore, plastic limit obtained by rolling-thread method is event less quantifiable than liquid limit obtained by Casagrande apparatus or fall cone penetrometer.

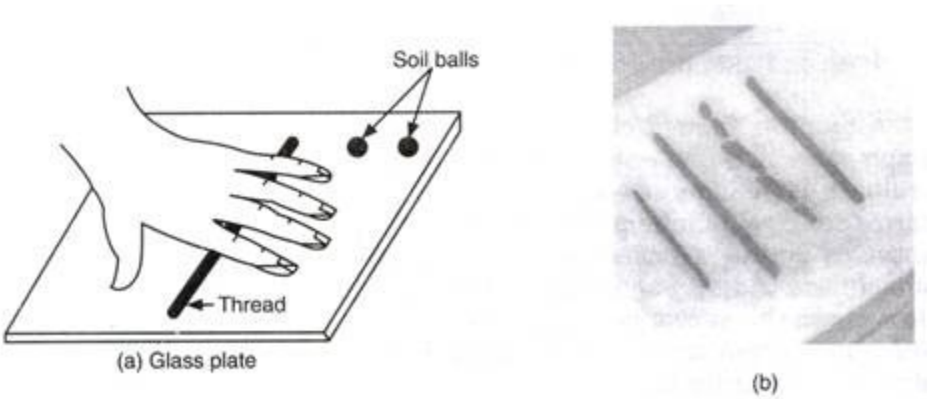


Figure 8: Rolling thread method, performed by rolling sol balls into threads (a) until they reach their plastic limit and break (b).

3.4.2. Mud machine method (MDM)

There have been many attempts to perfect tests for plastic limit, in order to obtain more reliable and reproducible results. Most of such endeavors focused on using fall cone penetrometer to determine plastic limit as well, not just liquid limit. However, studies have shown that even though this method can be pursued, the value obtained does not represent the true plastic limit. On the other hand, some scientists have tried to use reverse extrusion method and one apparatus to determine both plastic and liquid limit, which has proven to be more reliable method. This implies that most attempts focused on suggesting single apparatus to determine both consistency limits. For example, using extrusion method, plastic limit can be predicted and can be used to assess liquid limit as well. Study by Kayabali (2012), suggested that about 90% of plastic and liquid limit can be predicted with accuracy of plus/minus 10% error, using reverse extrusion test. In this technique, LL and PL were represented as water contents which correspond to specific extrusion pressures. Today, there is another alternative to this method, called mud press machine (MPM), as seen on Figure 9. This newly developed method consists of tool which is miniature multi-hole direct extrusion machine. Study conducted by Kayabali et al., (2016), see Figure 10, used this new method. Liquid limits obtained with this tool had great degree of accuracy, which was somewhat lower for plastic limit. This method eliminates second set of apparatus in order to conduct an experiment and operator. Because a single apparatus is used, and operator is not needed, operator dependency and experience are not important factors anymore. The test duration is remarkably short, again attributing to the fact that one apparatus is needed. This factor becomes especially important for the construction purposes, because the results are needed in very short timeframe, so that the engineering companies do not lose their money resources, besides human and time resources as well. In the end, authors argue that the cost to manufacture this apparatus is very low, and because it is very light and simple, it can be placed anywhere in the laboratory.

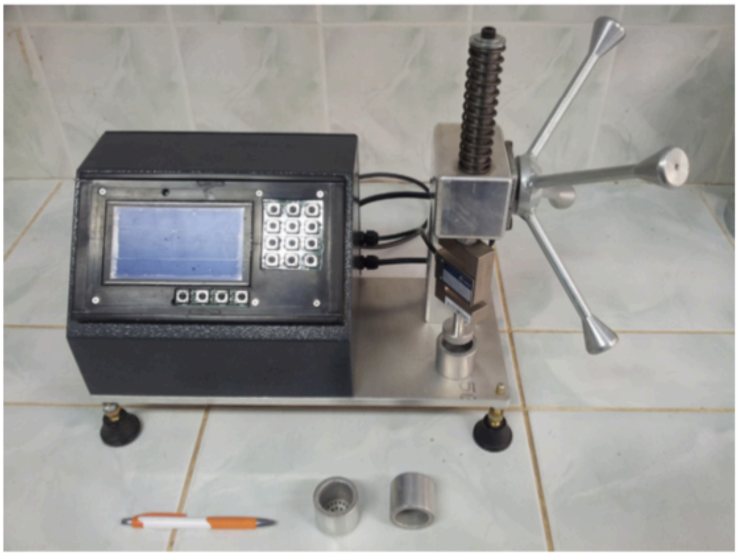


Figure 9: Mud press machine used by Kayabali et al., (2016).

For the purpose of this paper, only rolling thread method was conducted in order to determine plastic limit.

3.5. Shrinkage limit (SL)

When soil crosses its state from being liquid to solid, there are three characteristics, limiting water contents. The lowest limiting water content is the shrinkage limit, while the first two are the free-swell limit and the settling limit. Shrinkage is the process of volume reduction which takes place due to capillary pressures generated through evaporation of water from the soil. As the evaporation continues, the radius of meniscus developed in water in every pore continues to decrease. This process advances until the shear stresses induced by the capillary pressures are equalized by the shear strength at the particle level. The particle size distribution plays an important role in shrinkage process, because the larger void spaces between sand particles are filled with finer sand and silt particles, while smaller void spaces between silt particles are filled by finer clay particles. Hence, we can state that shrinkage is a packing phenomenon observed in soil and is primarily controlled by particle size distribution of the soil (Sridharan and Prakash, 2000). Shrinkage limit (SL) is the limit which separates the solid from semi-solid state in soils. At this specific water content, soil remains rigid or nearly constant although water is totally lost from the soil.

4. Materials and Methods

4.1. Study area

Samples were taken from three locations in Czech Republic: Suchdol, Uhříněves and Ruzyně. All three locations are found in Prague – Suchdol and Ruzyně are located in Prague 6, while Uhříněves is part of Prague 22. Prague, as the capital city of Czech Republic, is very attractive location for numerous engineering endeavors. Because of this important construction potential, it is extremely crucial that the soil is assessed in the proper way before the construction work start. Such soil survey can significantly reduce costs and labor and help to avoid any problems during construction process. The criteria for soil was that it should be suitable for construction purposes (not necessarily agricultural ones) and that it is not in close proximity to water source, as soil would be too liquid in this case, and it would be very difficult to analyze the liquid limit. Additionally, sandy soils would not be suitable for this type for survey, because this type of soil is not suitable for the construction purposes. The reason for this is that sandy soils have large particles and cannot hold water. Besides this, such soils are often acidic, which can pose significant problems for any constructions.

Below, there is summary of three study areas used for analysis of Atterberg's limits:

Uhříněves (50°2'0.4"N, 14°36'32"E) is located in Prague 22, at 295 m a.s.l., and is known as sugar beet region. The average annual temperature at this location is 8.4 °C and annual precipitation is 575 mm. The soil type at this locality is Cambisol and soil texture is clay loam with an organic matter content in range of 1.74-2.12%. pH is neutral and soil acts as storage of all essential nutrients (Dvořák and Král, 2019).

Suchdol (50°8'N, 14°23'E) is located in Prague 6, at 286 m a.s.l. The soil type at this locality is loamy carbonate Haplic Chernozem (IUSS Working Group WRB, 2015) with prevailing loamy texture. The average annual precipitation and temperature are 495 mm and 9.1°C (Doležal et al., 2012).

Ruzyně (50°05'17.264"N, 14°17'50.024"E) is located in Prague 6, at 340 m a.s.l., and is beet production area. The annual precipitation is 472 mm and annual average temperature 8.4°C. The soil texture of the experimental field is silty clay loam and the soil was classified as Orthic Luvisol (Mühlbachová et al., 2015; Báťková, et al., 2020).

4.2. Sampling and sample preparation

Disturbed samples have been obtained for this analysis. This type of sample is collected to determine soil type, classification, consistency, density and similar properties. Method for obtaining of disturbed samples used was hand excavation, using shovel. Samples have been taken as bulk specimens, approximately 12 liters per each sample. This amount was necessary to be collected in order to obtain representative soil sample for analysis.

After sampling, samples have been brought to lab in order to be air-dried for at least two weeks. Samples were placed on sheets of white paper and distributed on them in equal portions. As visible on Figure 10, large pieces of rocks, plant roots, small branches, insects and small worms have been removed from the sample and placed in separate bowl, which was discarded after. The purpose for this step is to remove the skeleton (particles which are larger than 2 mm), from soft earth materials, which would be used for analysis.

Figure 10: Removed plant roots, branches, stones and insects from soil samples (left). Soil samples left to air-dry on white sheets of paper (right).

After air-drying, samples have been processed and grinded through mill, and then sieved through 0.4- and 0.5-mm sieves, in order to obtain fine earth particles. Approximately 500 grams of each soil sample has been sieved through 2 mm sieve and sealed in plastic bag, for future particle density, particle size distribution, pH and electrical conductivity analyses (see Figure 12).

It is important to mention that excess of soil, which was not used for analysis, was returned back to field for recovery and recultivation purposes. The soil waste was never thrown away and destroyed. Because soil sampling can modify the soil nature, in terms of microbial life especially, the intent was to reduce this effect as much as possible.

4.3. Soil particle density determination

Soil particle density determination is important analysis to understand better chemical and physical properties of soil. Particle density is the density of the soil particles which collectively make up a soil sample. The common range of particle density in soils is 2.55 to 2.70 g cm^{-3}. The particle density of a soil measures the mass of a soil sample in a given volume of particles.

Standard water pycnometer method according to CEN ISO/TS 17892-3 was employed. Vacuuming or boiling were used for air-bubbles removal, according to the availability of devices in laboratory. Three replicates were taken for each sample.

4.3.1. Vacuuming method

Procedure took place as follows:

1. A balance was used to obtain approximately 15 grams of air-dried soil. The sample was then transferred to pycnometer. It is important to mix soil before weighing and transferring to pycnometer in order to homogenize it, as well as to clean the funnel and spoon between samples, in order to prevent mixing the samples.
2. Pycnometers with soil samples were transferred to oven and heated at 105 °C for 2 hours. Oven-dried samples with pycnometer were weighted after this time.
3. Small amount of distilled water was added to soil. This was done very carefully, by slow addition of distilled water on walls of pycnometer, in order to prevent destroying of micropores, as well as to prevent any soil sample loss from pycnometer (see Figure 11).
4. Samples were placed in desiccator, with lid on top, to prevent any loss from samples due to high pressure inside the desiccator. Desiccation process took 2 hours.
5. Pycnometers were taken out and deaired water was added.
6. The desiccator was closed, and vacuum was switched on for 1 hour.
7. The pycnometers were taken out from desiccator, filled with degassed distilled water and then transferred to tempering bath.

8. After tempering, samples have been weighted again.
9. At the end of the experiment, the soil suspension was discarded, and equipment was carefully washed.

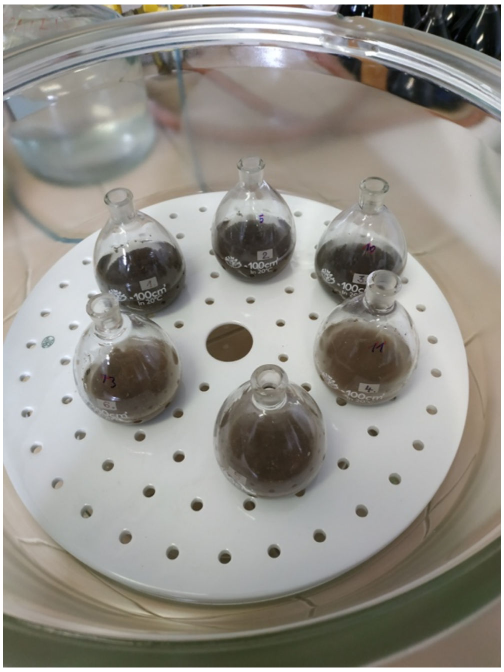


Figure 11: Pycnometers with soil samples and distilled water ready for vacuuming.

4.3.2. Water pycnometer method

Procedure took place as follows:

1. A water pycnometer is filled with deaired distilled water up to the top of its neck and placed in the water tempering bath to reach temperature marked on the pycnometer (usually 20 °C). The stopper is carefully inserted in the neck of the pycnometer and any excess water is allowed to overflow, so that there are no air bubbles below the stopper. The volume of pycnometer should be exactly 100 cm^3. The pycnometer is then taken out, dried, cleaned and weighted. Mass is marked as m_1.
2. A balance is used to obtain 15 g of sample, which was previously grinded through 2 mm sieve and dried at 105 °C.
3. A small porcelain bowl is filled with the soil sample and distilled water so that soil is about 0.5 cm below the water level.
4. The soil with water is then gently boiled and permanently stirred for about 5 minutes to remove the entrapped air.

5. Water was poured out from the pycnometer. Pycnometer was then filled with soil and water mixture which was previously boiled (see Figure 12). All soil which remained on bowl, glass rod and operator's fingers was carefully washed to pycnometer, with as little water as possible.
6. The pycnometer is filled up with deaired distilled water and tempered to reach required temperature. Masses of pycnometers are taken as m_2.
7. At the end of the experiment, the soil suspension was discarded, and equipment was carefully washed.

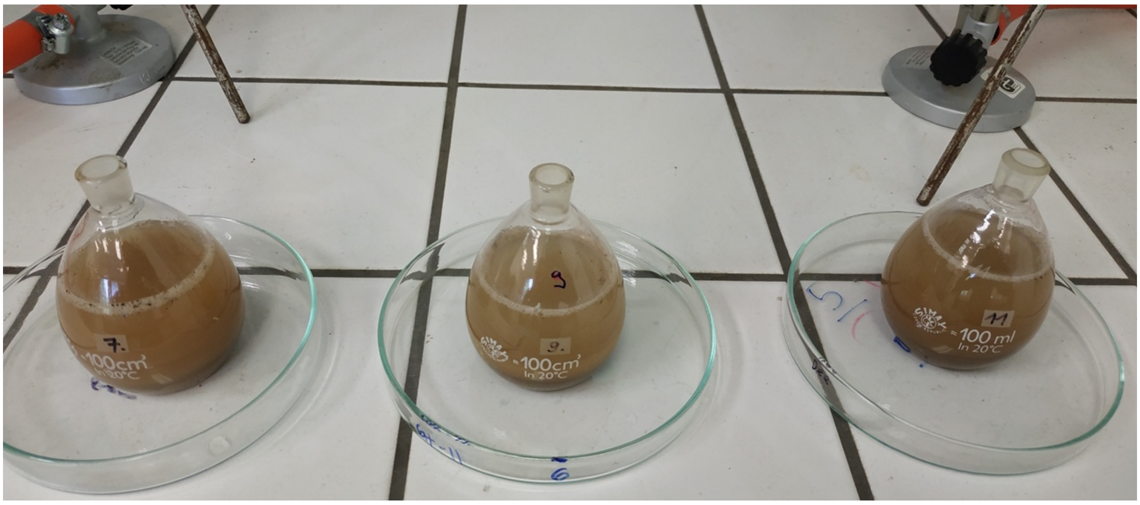


Figure 12: Pycnometers with boiled soil sample and water – water pycnometer method.

4.4. Particle size distribution determination

Textural class of soil can be easily determined by the "feel" method, which involves forming a moist soil sample in ball and squeezing it between the thumb and index finger in order to form a ribbon. The texture can be detected by ribbon length (if it can be formed at all) and smoothness of sample. This method is especially valuable for field experiment, or if immediate determination is needed (Schoonover and Crim, 2015).

The purpose of particle size distribution analysis is to evaluate and measure distribution of different sizes of soil particles. In this way, it is easy to determine soil textural class. For particle size distribution, two methods were used: hydrometer analysis and wet sieving. In hydrometer analysis, fine-grained soils, silts and clays, are graded. With wet sieving, bulk materials of different kinds are separated into size fractions.

4.4.1. Hydrometer method

Hydrometer is an instrument used to measure the relative density of liquids. The method is based on Stoke's law governing the rate of sedimentation of soil particles suspended in water. However, this method is time-consuming and requires certain equipment (Schoonover and Crim, 2015).

Sand has the largest particle size, silt is intermediate in size, while clay is the smallest soil particle. When mixture of particle sizes is suspended in column of water, particles which are heavy and large will settle first. This means that when soil sample mixture is stirred or shaken, sand particles will settle at the bottom of the cylinder almost immediately, while silt and clay particles will stay in the suspension. After some time, silt particles will eventually settle as well, so that only clay particles are left in suspension. Hydrometer readings (see Figure 13) will be taken in exact time intervals, over the period of 48 hours, keeping the temperature as constant as possible. After the readings are taken, the exact percentages of sand, silt and clay can be calculated, so that the textural class of soil can be determined.

Hydrometer (sedimentation) method took place according to ČSN EN ISO 17892-4 standard.

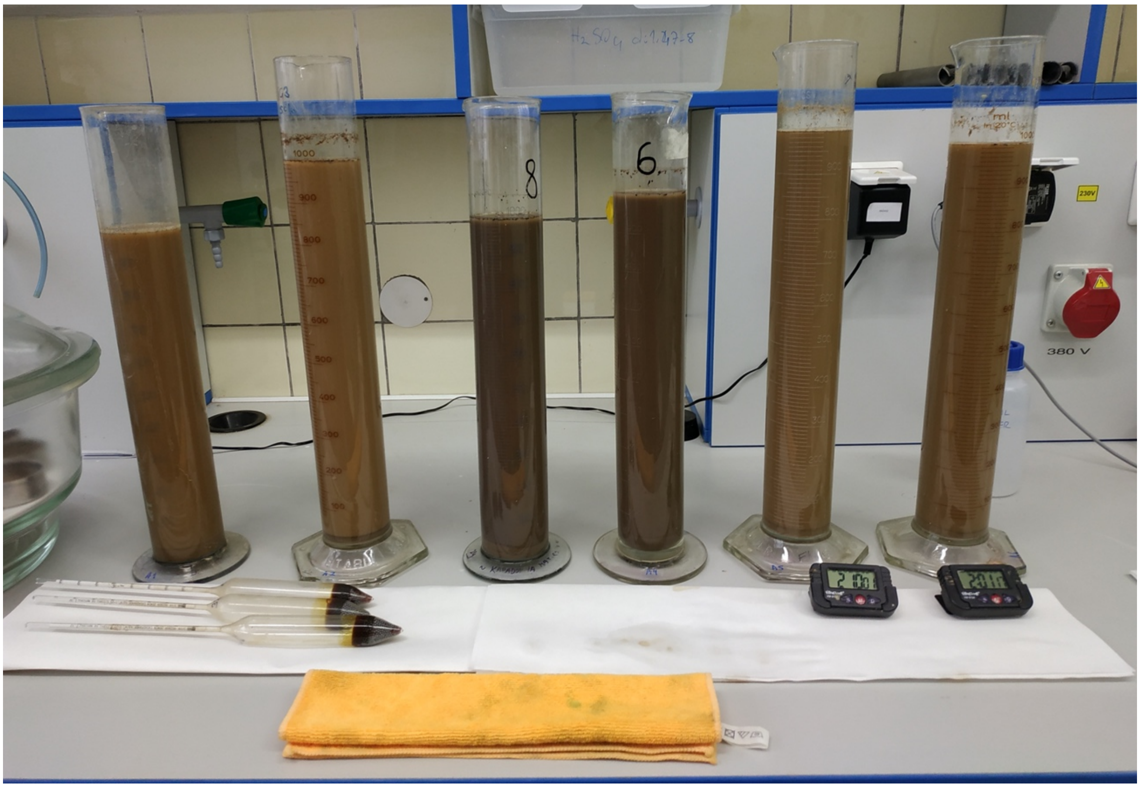


Figure 13: Hydrometer readings of samples.

Two replicates were taken for each sample, yielding six samples in total. One replicate from Ruzyně sample was destroyed because ethanol was added instead of distilled water.

4.4.2. Wet sieving method

Wet sieving method took place after hydrometer analysis was finished. Just like with hydrometer method, one replicate (from Ruzyně sample) was not measured, because ethanol was put inside by accident.

This method has been conducted using four sieves with different diameters: 1 mm, 0.5 mm, 0.1 mm and 0.063 mm (see Figure 14). The soil was allowed to pass through sieves of different diameters, so that the masses and contents of soil particles with different sizes can be easily calculated.

Figure 14: Four sieves with different diameters (1, 0.5, 0.1 and 0.063 mm) placed on top of each other, so that soil can be passed through them.

4.5. pH and electrical conductivity determination

Soil pH is scale which measures acidity or alkalinity of soils and it ranges from 0 to 14. Neutral soils have value of 7, acidic soils have values below 7 and soils which are basic or alkaline have pH values higher than 7. Extreme acidity or alkalinity can induce changes in soil behavior, especially due to rapid development of cities and industries. Sources of acidity are usually vehicular or industrial deposits, precipitation with high content of SO_x, NO_x and CO_x particles, and mining activities. On the other hand, alkalinity is caused by mineral deposits due to liming, which can produce saline soils.

Soil sensitivity to pH changes depend on several factors: presence or absence of carbonates, total cation exchange capacity (CEC), content of clay and organic matter in the soil. Results shown by Momeni et al. (2020) state that low pH values indicate increase in liquid limit and plasticity index. Therefore, it is important to assess effects of alkalinity or acidity present in the soil, as pH will have great effects on Atterberg's limits and hence on geotechnical and engineering properties of soil.

Electrical conductivity (EC) of soil is measurement of how much electrical current soil can conduct. Clayey soils can conduct more current than silty and sandy soils, because clay particles are smaller and can hold more water than sand and silt. It is the most common measure of soil salinity.

Both pH and electrical conductivity have been tested from the exact same prepared samples from the three localities (see Figure 15).

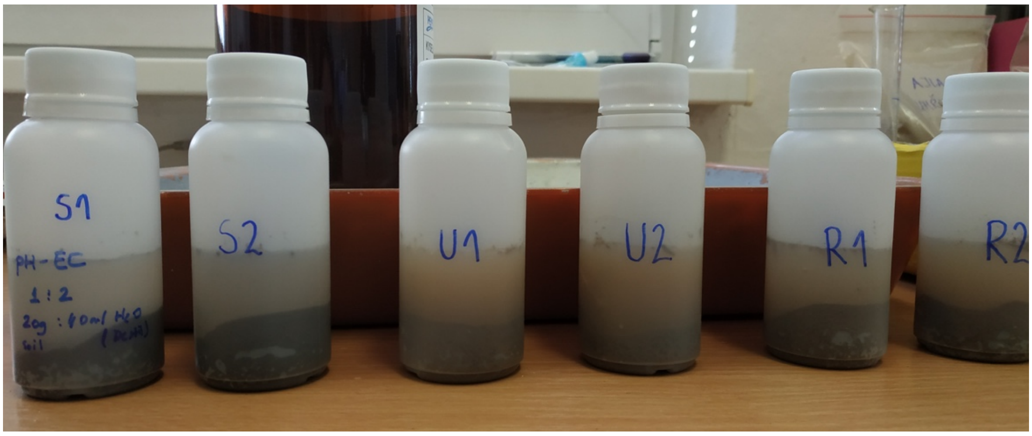


Figure 15: Soil samples inside plastic bottles ready for pH and EC analysis.

4.6. Plastic limit determination

In order to determine the plastic limit, samples with 0.5 mm diameter were taken. In total, there have been 30 samples; 10 samples for each locality. Procedure went as follows:

1. Approximately 30 g of soil (±1 g) was weighted and placed into bowl.
2. Water was added and kneaded into firm paste.
3. From that paste, two bigger balls were formed, and each of them was divided into four additional smaller balls. One set of four balls belongs to one sample.
4. Each ball was rolled to cylindrical thread, or „snake“ of 3 mm in diameter on smooth glass plate (see Figure 16, top).
5. Sample was rolled until it fell apart, delaminated as tube or formed small barrels.
6. Broken pieces from entire thread were placed in sampling container (see Figure 16, bottom) and cover was closed to protect any water from soil to evaporate.
7. Containers with soil samples were weighted and then taken to oven to dry at 105 °C. After that, they were placed into dessicator and then weighted again.

Figure 16: Plastic limit determination by rolling thread method (top) and soil samples after reaching their plastic limit, resulting in their disintegration into smaller pieces (bottom).

In total, 10 replications of experiment were taken for every soil sample. However, first two were taken as trial, to check if experiment should be repeated or not.

4.7. Liquid limit determination

Liquid limit was determined by two methods: Casagrande apparatus and cone penetrometer. In total, 144 samples were obtained for LL experiments; 72 for the Casagrande apparatus and 72 for the cone penetrometer. Four samples were needed for one liquid limit. Liquid limit for each locality was determined in 6 repetitions, three with sieve 0.5 mm and three with sieve 0.4 mm.

Detailed protocol for respective methods will be described below. All devices and procedures are in accordance with the technical standard CEN ISO/TS 17892-12.

4.7.1. Casagrande apparatus

Before experiments took place, equipment needed to be set up and calibrated in the following way:

1. It was verified that the Casagrande cup will fall from 1 cm.
2. It was made sure that the adjusting screws are tight.

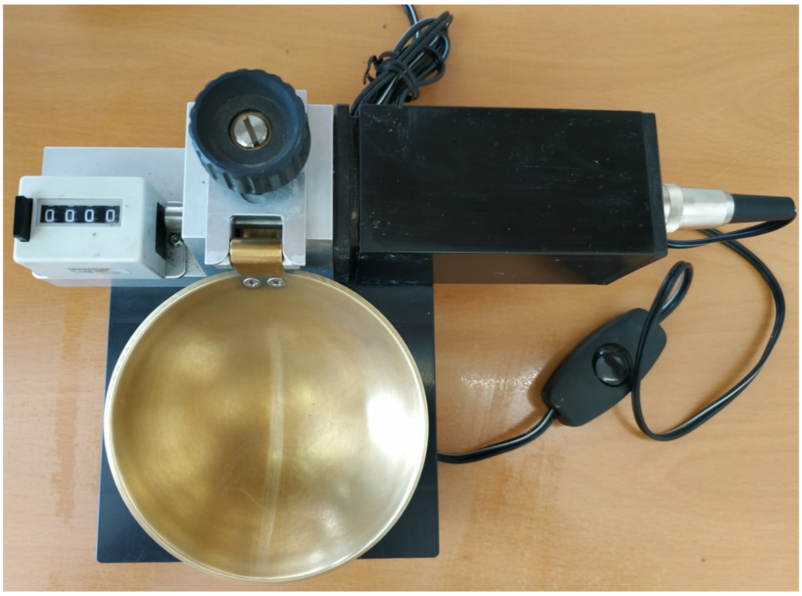


Figure 17: Casagrande apparatus after setting up and calibration, ready for experiment.

After equipment set up (see Figure 17), sample preparation took place and the experiment started:

1. Approximately 350 g of soil was placed in the mixing bowl. Water was added and thoroughly mixed homogenize the sample. It was left for approximately 30 minutes and covered with plastic bag to eliminate the drying out of the sample.
2. Soil was smoothened to uniform thickness and placed on the percussion cup (see Figure 18, top left).
3. The tool is held perpendicular to the inside surface of the cup, bevelled edge toward the front and single-cut groove was cut through the sample (see Figure 18, top right).
4. The apparatus was allowed to start, and stopped until the groove closed at 12.5 mm. The first result should be in the range 30-35 drops.
5. Approximately 15g of soil around the closed groove was taken out (see Figure 18, bottom) and placed in sampling container. The value was measured.
6. The sampling cup was taken to oven for drying, after which results were measured again.

Figure 18: Experiment with Casagrande apparatus: smoothened soil on Casagrande cup (top left), cut-out groove (top right), taken-out soil around the closed groove (bottom).

It is important to state that all measurements should be in range between 35 and 15 drops. If the first drop count was higher than 35, the sample was returned to the mixing bowl and little water was added.

4.7.2. Cone penetrometer

Before experiments took place, equipment needed to be set up and calibrated (see Figure 19). New, standardized cone (80g/30°) was added on penetrometer.

Figure 19: Cone penetrometer after setting up and calibration, ready for experiment.

1. From the same mixing bowl, sampling cup was filled with soil paste, making sure there are no air bubbles. The soil surface was cut with a knife to be smooth.
2. The sampling cup with the soil paste was placed under the cone. It was lowered exactly to touch the soil surface, in the middle of the cup (see Figure 20, left).
3. The cone was released and let to penetrate for 5 seconds (see Figure 20, right).
4. The depth of penetration was measured with accuracy of 0.1 mm. Approximately 15g of soil surrounding the penetration zone was taken out and placed in sampling container. The value was measured.
5. The sampling cup was taken to oven for drying, after which results were measured again.

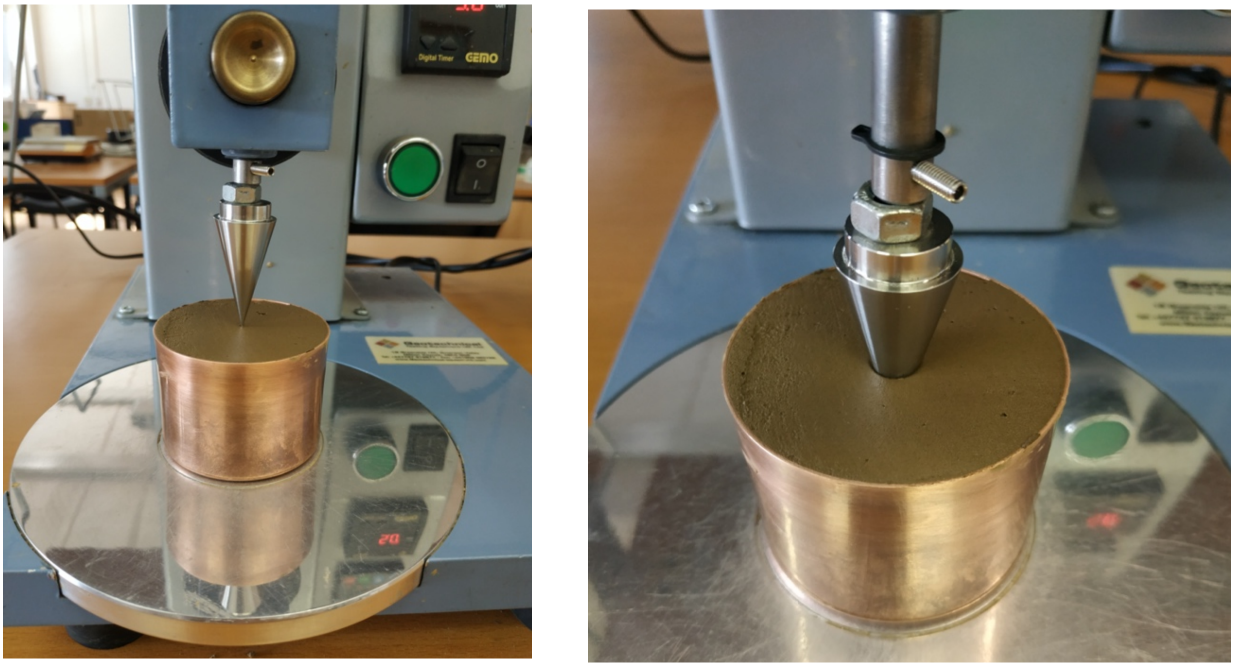


Figure 20: Lowered cone touching the surface (left) and penetrated cone (right).

It is important to state that all measurements should be in range between 15 and 25 mm of penetration depth. If the first penetration value was lower than 15, the sample was returned to the mixing bowl and little water was added.

4.8. Index of plasticity

The index of plasticity (IP) is a measure of the plasticity of a soil. The index of plasticity is the rnge of water contents where the soil exhibits plastic properties. It is calculated as follows:

IP = LL – PL

Where IP is index of plasticity (g/g), LL is liquid limit (g/g) and PL is plastic limit (g/g). classification of soil according to the IP can be done according to Sowers (1979), values are given in mass %:

(0) Non-plastic – (<7) Slightly plastic – (7-17) – Medium plastic – (>17) – Highly plastic

4.9. Statistical analysis

All obtained values were statistically analysed by descriptive statistic such as arithmetic mean, standard deviation, coefficient of variation (CV) and analysis of variance (ANOVA). Calculations were done in MS Excel or Statistica (TIBCO Software Inc., v. 13.3).

5. Results

5.1. Soil particle density determination

Soil particle density was determined by vacuuming method for Suchdol and Uhříněves samples, while water pycnometer method has been used for Ruzyně samples. Three replicates have been used for each locality.

Using the data obtained from the experiments, particle density was calculated, as well as dry amount of 50 g of soil, which was used for particle size distribution analysis. It was concluded all samples had similar particle density (see Table 3). Suchdol sample had slightly lowest density, while Uhříněves had the highest value of particle density.

Table 3: Calculation of particle density and dry amount of soil for all three localities.

Locality	**Method**	**Particle density (g/cm^3)**
Ruzyně	Boiling	2.65
		2.61
		2.63
Suchdol	Vacuuming	2.62
		2.60
		2.76
Uhříněves		2.66
		2.73
		2.47

5.2. pH and electrical conductivity

All three samples have been tested for pH and electrical conductivity, with two replicates for each locality. Results in Table 4 showed that the most acidic soil was from Uhříněves, while Suchdol had the most alkaline pH. Ruzyně soil was the closest one to the neutral pH, although it was very close to value of Suchdol soil. However, this difference was a lot larger when it comes to electrical conductivity analysis. Suchdol soil had highest EC values, which can be connected to the most alkaline pH values of the three samples. Conversely, Uhříněves soil which had the most acidic pH, had lowest EC values. Compared with typical range for silt loam soil (see Figure 26), the salinity of all samples is negligible and thus had no influence on Atterberg's limits.

Table 4: Calculation of pH and electrical conductivity for all localities.

Sample	pH	Average pH	Electrical conductivity (µS/cm)	Average electrical conductivity (µS/cm)
Suchdol 1	7.83	7.80	225	223
Suchdol 2	7.78		221	
Uhříněves 1	6.74	6.745	177	180
Uhříněves 2	6.75		183	
Ruzyně 1	7.71	7.725	188	185.5
Ruzyně 2	7.74		183	

5.3. Particle size distribution

5.3.1. Hydrometer method

Before hydrometer readings took place, cylinder and hydrometer calibrations were measured, because not all cylinders had same measurements in terms of height and volume. Ten hydrometer readings were measured over the period of 48 hours. Readings of sample A-R1 did not take place, due to bubbling of sample, hence it was not included in results.

Temperature T (°C) was also measured together with hydrometer readings. Laboratory temperature was controlled. Temperature was slightly higher as two operators were working inside the laboratory, but after 2 hours of experiment, temperature got more stable, which was good for the measurements. Data has been collected and measured, to be subsequently used for calculations.

5.3.2. Wet sieving method

After soil was taken from hydrometer, it was placed in bowls and left to dry at 105 °C. Tares of empty bowls, as well as weight of bowls with dried samples have been measured.

Soil samples from hydrometer method have been passed through sieves with different diameters: 1 mm, 0.5 mm, 0.1 mm, 0.063 mm. Results were measured and noted down.

Masses of soil particles for each of sieves were measured and percentage have been calculated. From the Table 5, it can be observed that all localities had highest percentage of soil particles with diameter between 0.5 and 0.1 mm. Ruzyně samples had lowest percentage of soil particles in diameter lower than 0.063 mm, the same as half of the Suchdol samples (S2). In contrast, the other half of Suchdol samples (S1) and complete Uhříněves samples had lowest amount of soil particles larger than 1 mm. Uhříněves samples were consistent in the analysis, while Suchdol samples were not, which could imply a possibility of mistake in experiment. Additionally, Ruzyně samples were not fully complete, as sample R1 has been lost due to addition of ethanol by mistake.

Table 5: Mass and percentage of soil particles from all localities which passed through each of four sieves for wet sieving analysis.

Locality	Sieve diameter (mm)	Mass (g)	Percentage (%)
Ruzyně (R2)	>1	0.55	1.121
	0.5-1	0.6	1.232
	0.5-0.1	2.5	5.133
	0.1-0.063	0.92	1.889
	<0.063	0.13	0.267

Suchdol (S1)	>1	0.98	1.988
	0.5-1	2.01	4.094
	0.5-0.1	3.49	7.108
	0.1-0.063	1.71	3.483
	<0.063	1.05	2.138
Suchdol (S2)	>1	0.92	1.866
	0.5-1	1.83	3.727
	0.5-0.1	3.22	6.558
	0.1-0.063	1.18	2.403
	<0.063	0.27	0.550
Uhříněves (U1)	>1	0.17	0.344
	0.5-1	0.54	1.092
	0.5-0.1	2.9	5,866
	0.1-0.063	2.15	4.349
	<0.063	1	2.023
Uhříněves (U2)	>1	0.17	0.344
	0.5-1	0.51	1.032
	0.5-0.1	2.88	5.825
	0.1-0.063	2.37	4.794
	<0.063	0.7	1.416

Content of sand, silt and clay were calculated for every locality. Based on these calculations, particle size distribution (PSD) graphs have been constructed (Figures 21-23). USDA texture triangles (Figure 24) were used to determine soil texture class of each sample. It has been concluded that all soils had silt loam texture, with highest silt content and lowest amount of clay in all three localities (see Table 6).

Table 6: Calculation of sand, silt and clay content for all three localities and identification of soil texture.

Locality	Sand content (%)	Silt content (%)	Clay content (%)	Soil texture
Ruzyně (R2)	22.5	51.5	26	Silt loam
Suchdol (S1)	29	53	18	Silt loam
Suchdol (S2)	21	59	20	Silt loam
Uhříněves (U1)	30.5	51.5	18	Silt loam
Uhříněves U2)	20	62.5	17	Silt loam

Particle size distribution (PSD) graphs for all three localities can be seen on Figures 21, 22 and 23.

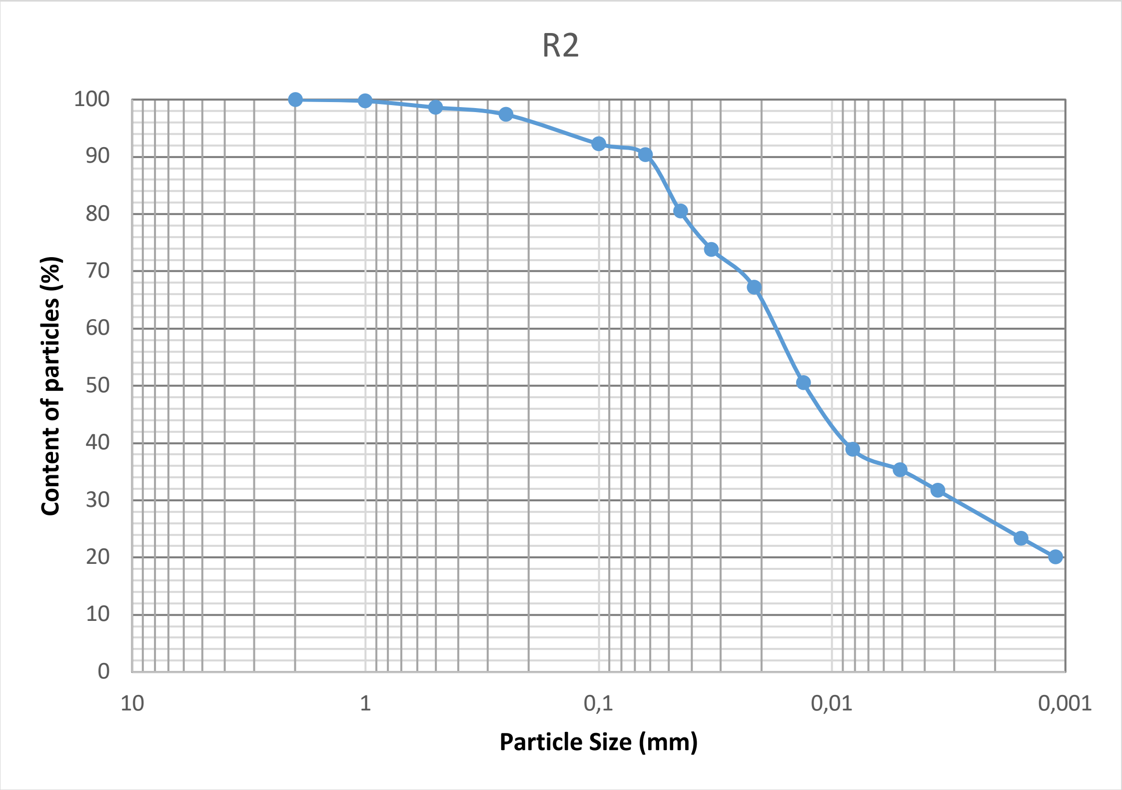
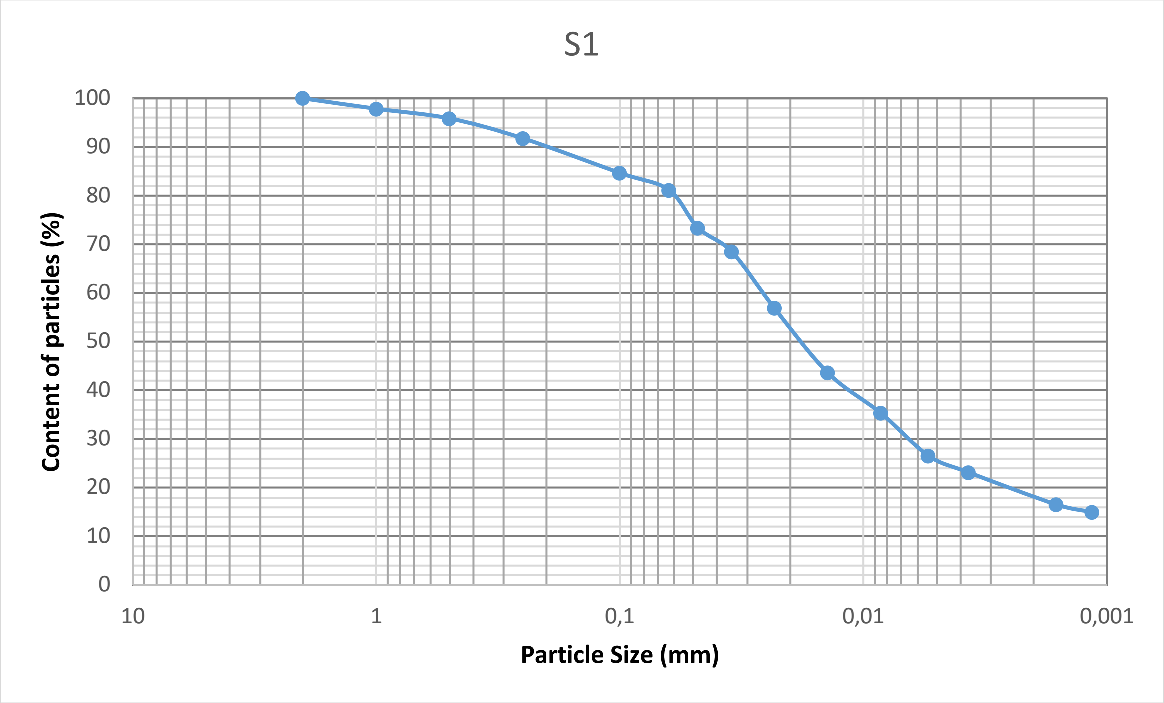


Figure 21: Particle size distribution graph for Ruzyně sample (R2).



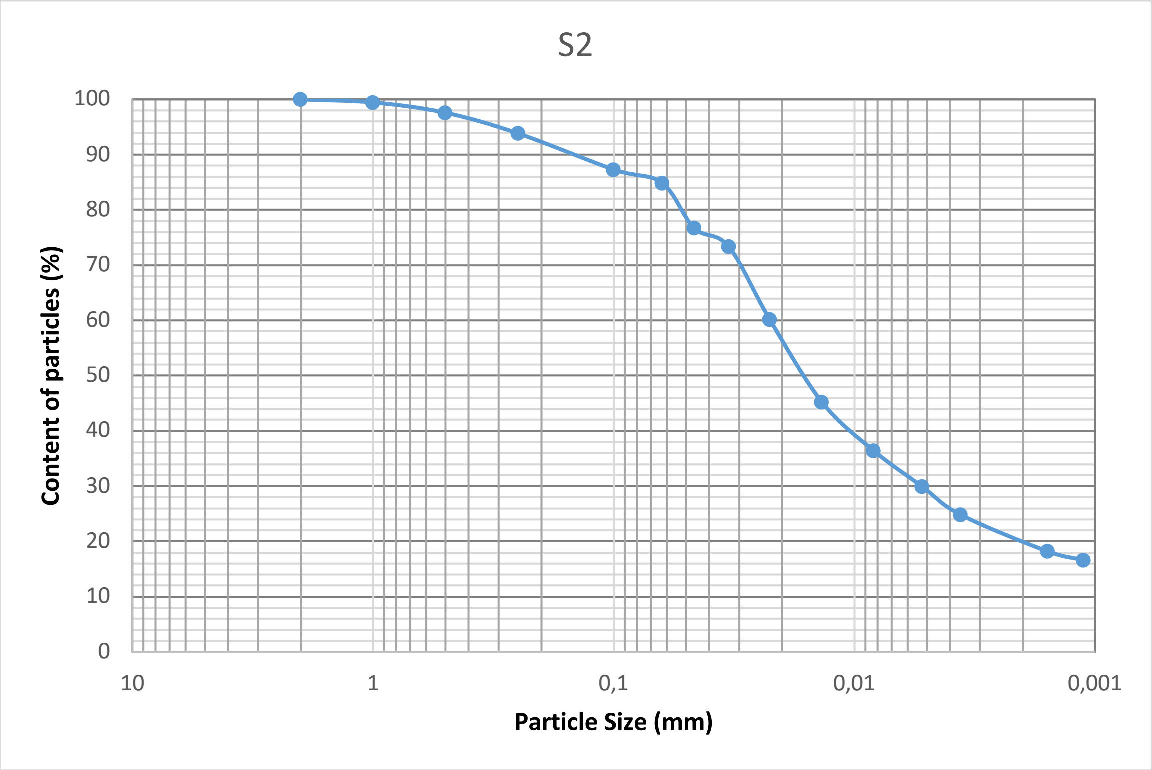
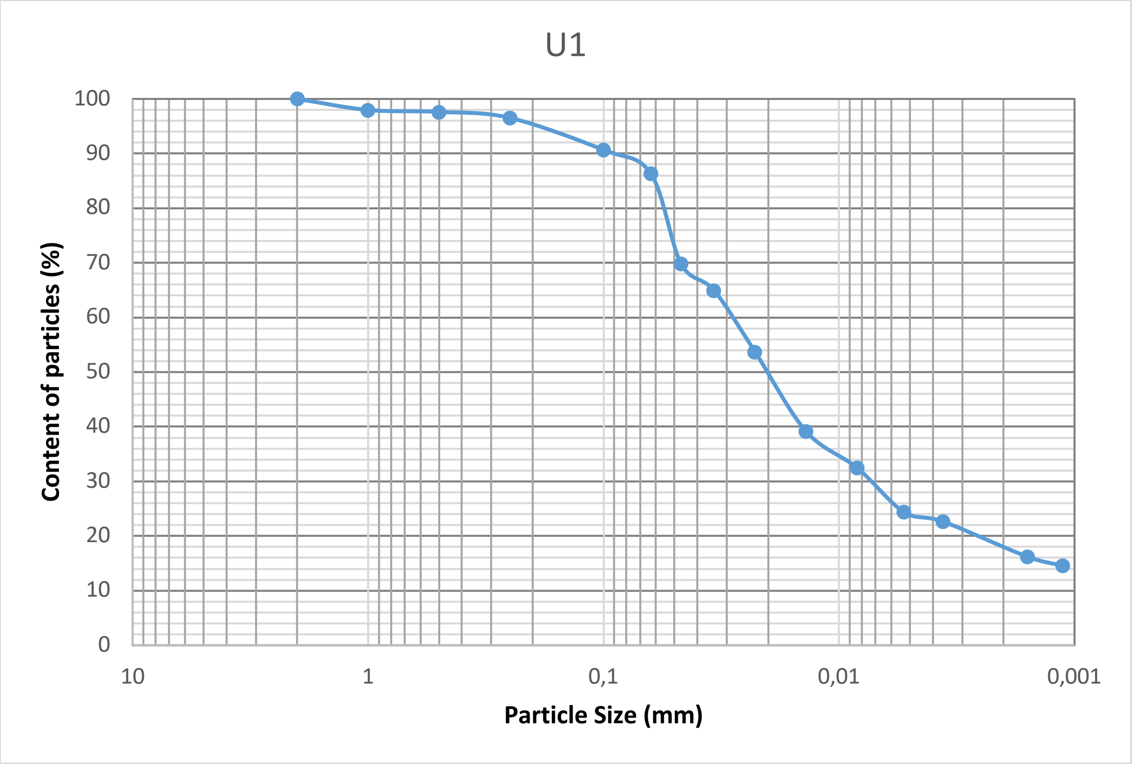


Figure 22: Particle size distribution graph for Suchdol samples (S1 and S2).



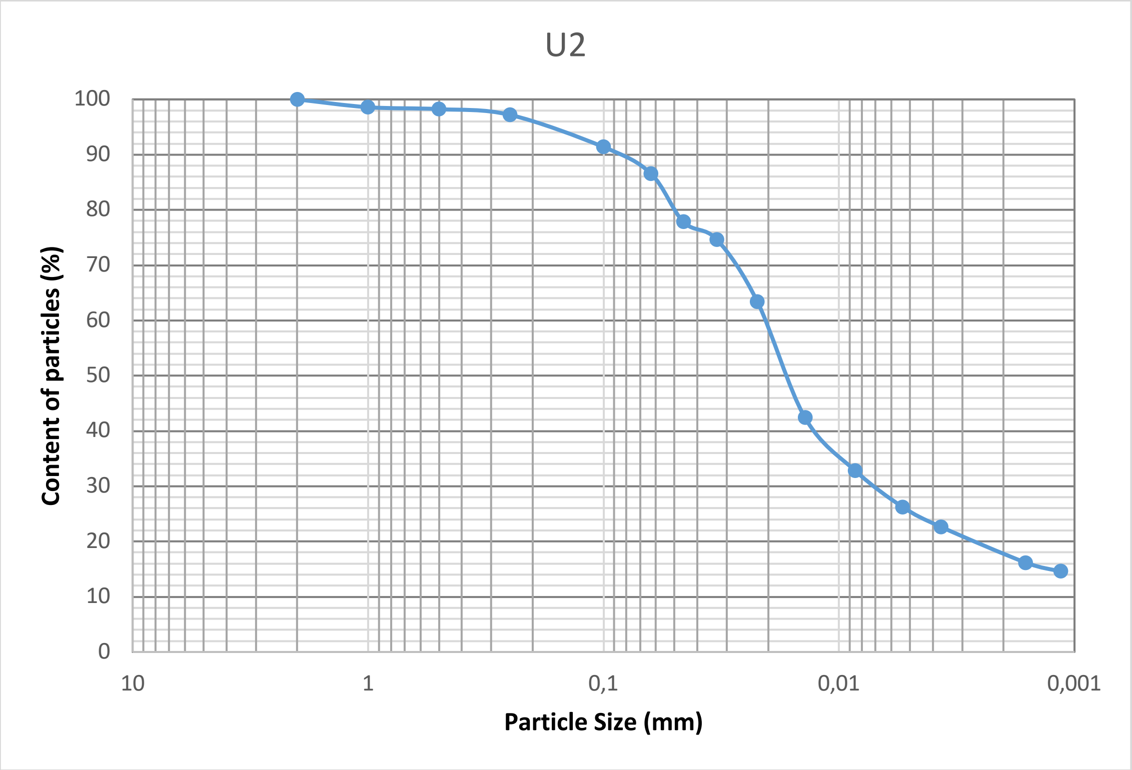


Figure 23: Particle size distribution graph for Uhříněves samples (U1 and U2).

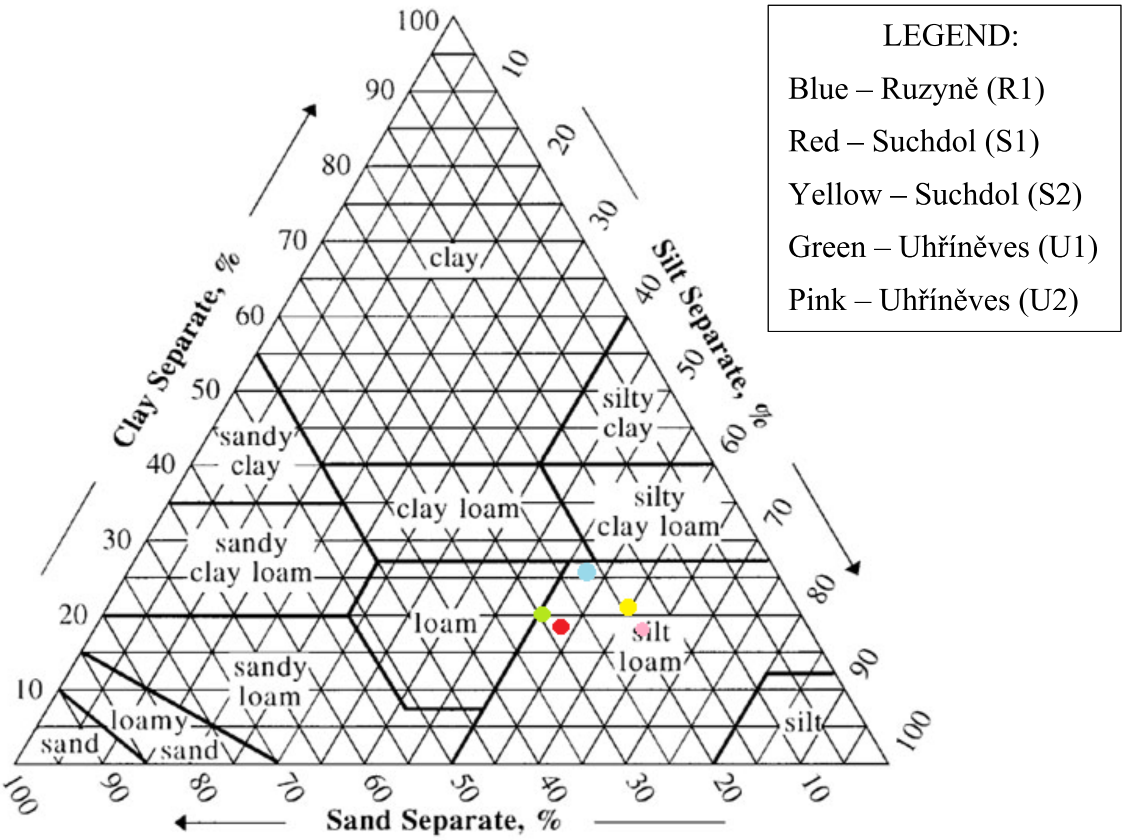


Figure 24: USDA texture graph for determination of soil texture for all three localities.

5.4. Plastic limit determination

Measurements of containers weight, as well as wet and dry samples have been taken for each locality. Dry sample mass for each sample has been calculated.

During experiment, observations on soil behavior were taken and noted down, as visible in Table 7. For example, it has been noted that Ruzyně soil tends to break down after 6-7 repetitions, while Suchdol soil breaks after 3-4 rolling repetitions and Uhříněves soil after 2-3 rolling repetitions. Suchdol soil required less water than Ruzyně soil, but Uhříněves soil needed lowest amount of water and was easiest to mold. Additionally, Ruzyně soil left a lot more residue on glass plate, compared to Suchdol and Uhříněves soils, which left almost no residue on glass surface. In contrast, Ruzyně soil did not leave dark residue on hands of the operator, compared to Suchdol and Uhříněves soils, which left dark brown and brown residues, respectively.

Table 7: Personal experience and observations while conducting plastic limit determination experiments and comparison between samples from different localities.

Locality	Ruzyně	Suchdol	Uhříněves
Number of rolling repetitions before soil breaks	6-7	3-4	2-3
Amount of water needed to be added to soil	Highest	Medium	Lowest
Residue on glass	Dark	No	No
Residue on operator's hands	Light brown	Dark brown	Brown

In order to test for plastic limit, ten repetitions were taken for each locality. However, in Ruzyně samples, two mistakes have been made and these two measurements (R2 and R5) have been excluded from the experiment. As noted in the Table 8, the results showed that Ruzyně soil has highest standard deviation and CV values. Additionally, Ruzyně soil showed lowest average water content from all three localities. On the other hand, Suchdol and Uhříněves soils have very similar average water content values, as well as standard deviation and CV. In general, all three localities show very similar plastic limit values. Based on t-test for independent samples, the plastic limits of Ruzyně and Uhříněves are significantly different at the level $p < 0.05$, while Ruzyně and Suchdol, and Suchdol and Uhříněves are not statistically different.

Table 8: Calculation of water content, standard deviation, coefficient of variation (CV), minimum, maximum and median values.

Locality	**Average water content (g)**	**Standard deviation**	**CV (%)**	**Minimum value**	**Maximum value**	**Median**
Ruzyně	0.2076	0.006564	3.2	0.1938	0.2059	0.2069
Suchdol	0.2123	0.002461	1.2	0.2084	0.2168	0.2121
Uhříněves	0.2141	0.002501	1.2	0.2090	0.2188	0.2138

To support the results visible in Table 7, the water content for plastic limit has been compared between three localities (see Figure 25). It is visible that Ruzyně samples had highest variability in results, especially because two samples have been removed and excluded from the experiment. Conversely, remaining two localities had rather stable variability in water content. With this information, the conclusion can be drawn that the experiments for Suchdol and Uhříněves can be more reliable for plastic limit determination.

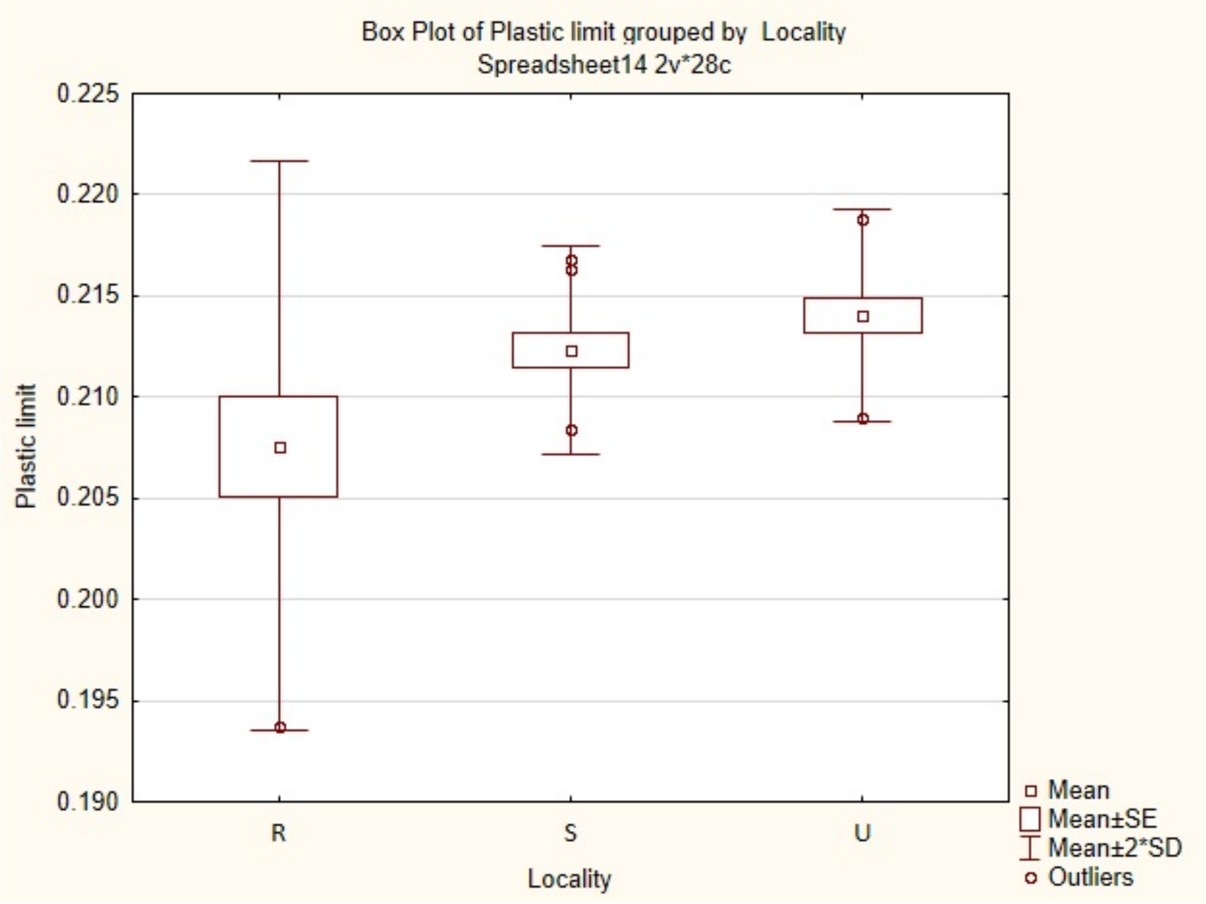


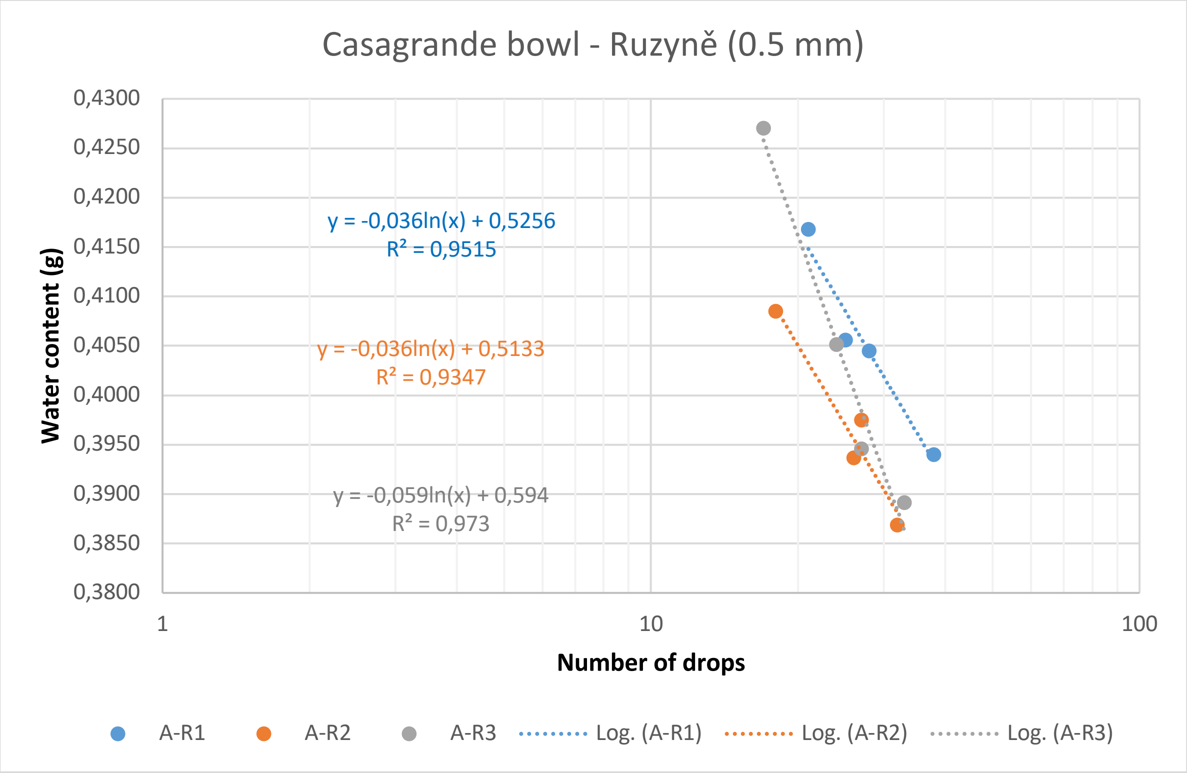
Figure 25: Comparison of water content for plastic limit between three localities.

5.5. Liquid limit determination

Both Casagrande bowl and cone penetrometer were tested with soil with 0.4- and 0.5-mm diameter. Liquid limit was calculated, as well as average values, standard deviation and CV.

5.5.1. Casagrande apparatus

Liquid limit graphs obtained by Casagrande bowl are presented in Figures 26, 27 and 28.



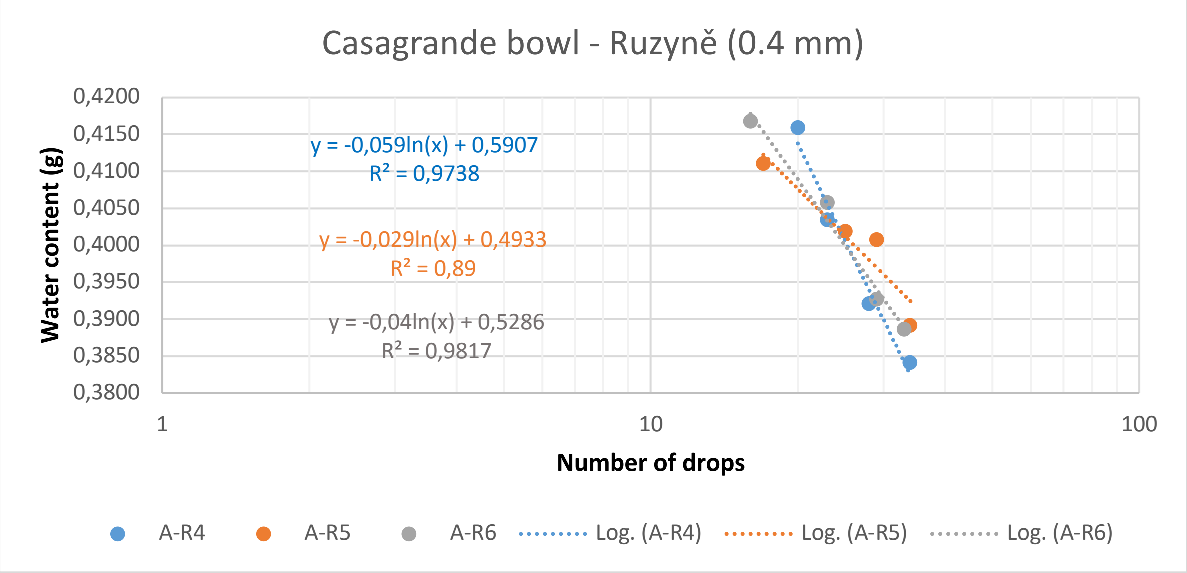
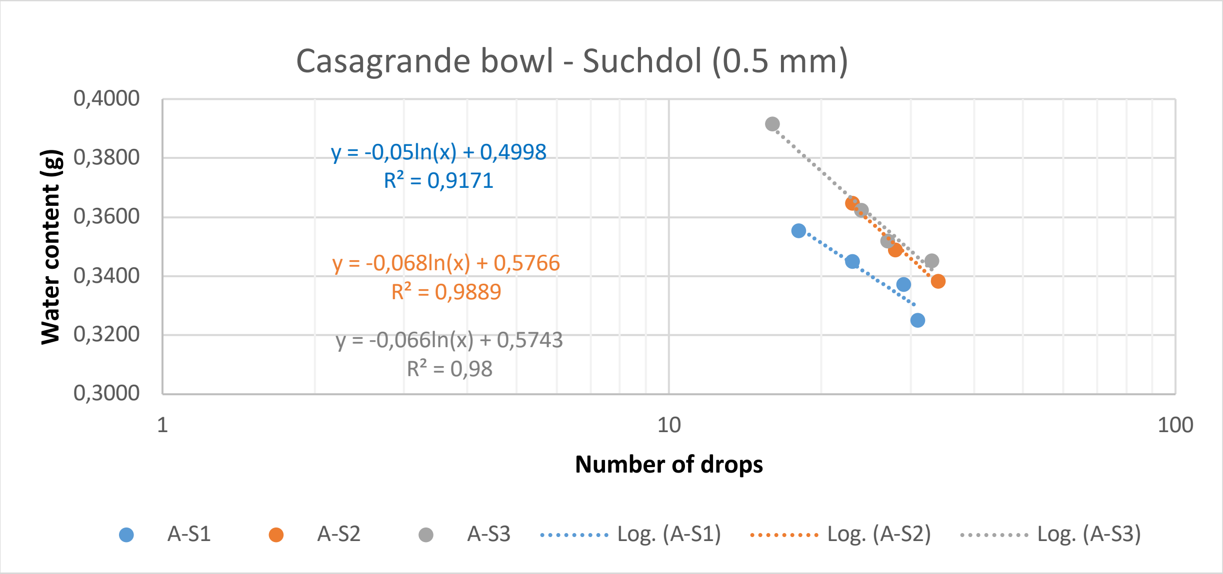


Figure 26: Liquid limit graphs by Casagrande apparatus for Ruzyně soil, using 0.4 mm diameter sieve (A-R1, A-R2 and A-R3) and 0.5 mm diameter sieve (A-R4, A-R5 and A-R6).



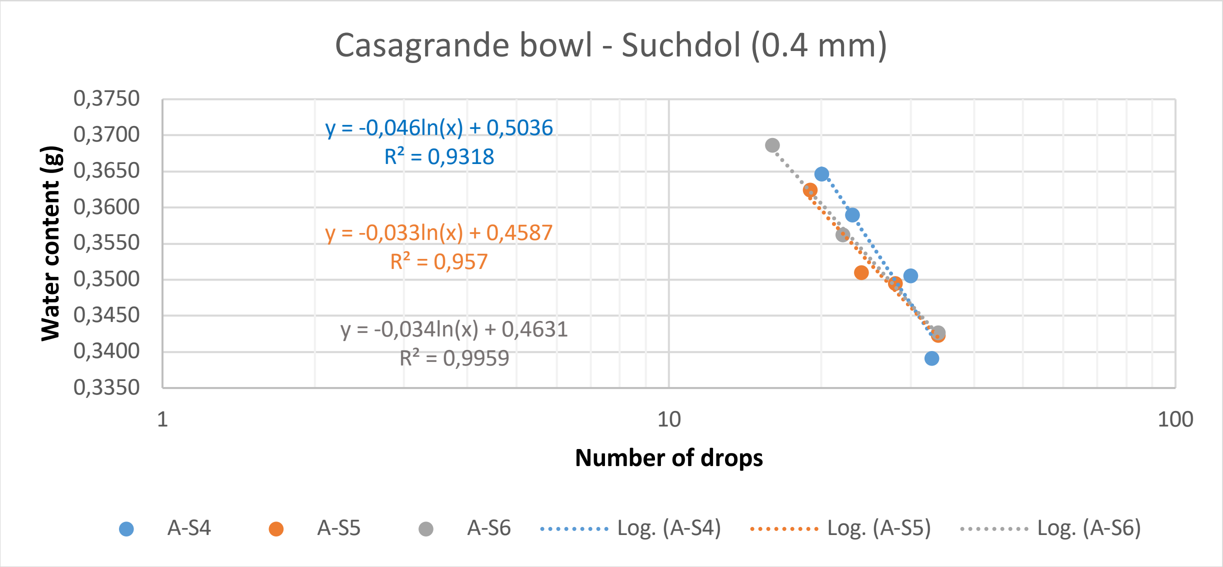


Figure 27: Liquid limit graphs by Casagrande apparatus for Suchdol soil, using 0.4 mm diameter sieve (A-S1, A-S2 and A-S3) and 0.5 mm diameter sieve (A-S4, A-S5 and A-S6).

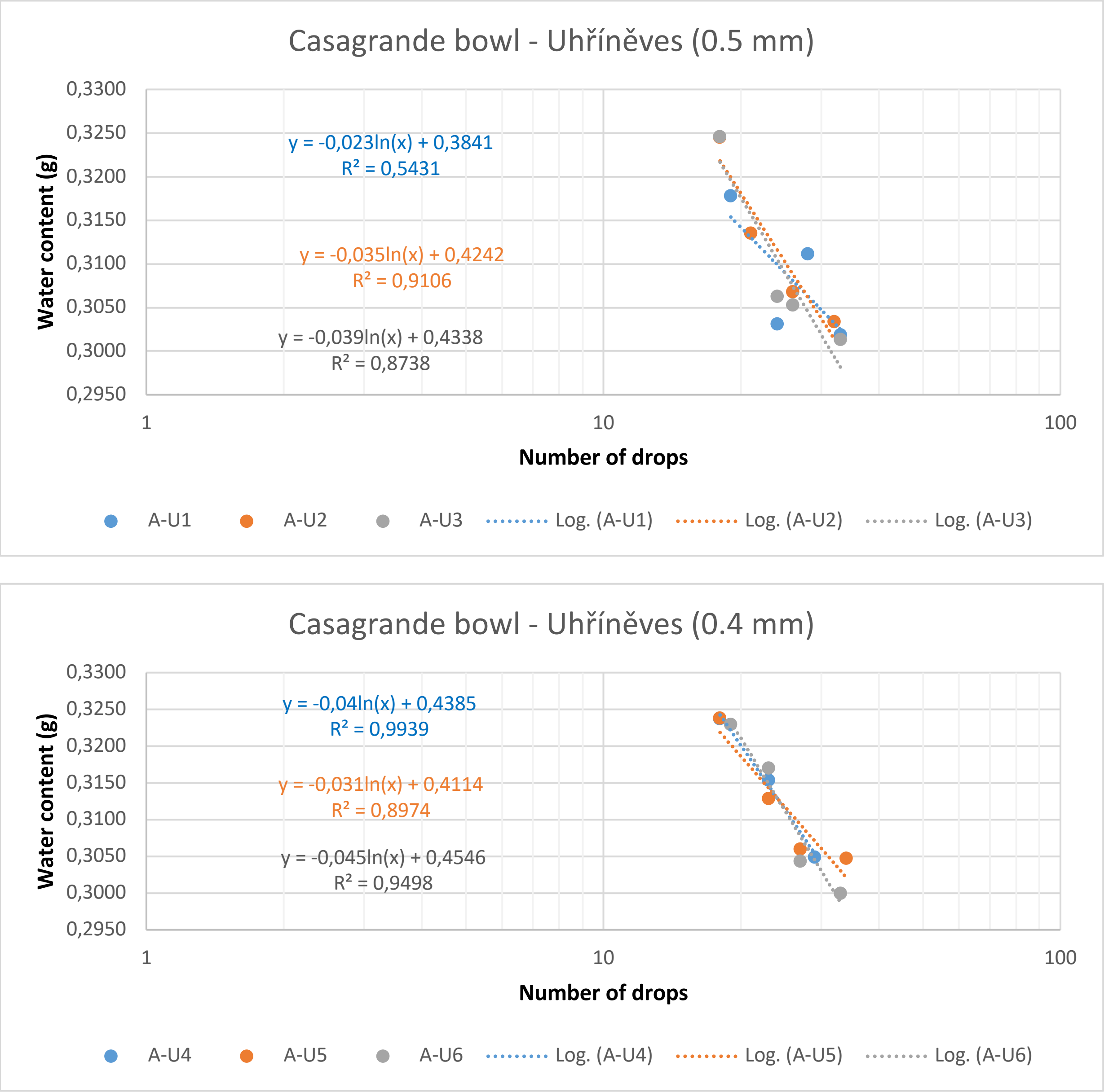


Figure 28: Liquid limit graphs by Casagrande apparatus for Uhříněves soil, using 0.4 mm diameter sieve (A-U1, A-U2 and A-U3) and 0.5 mm diameter sieve (A-U4, A-U5 and A-U6).

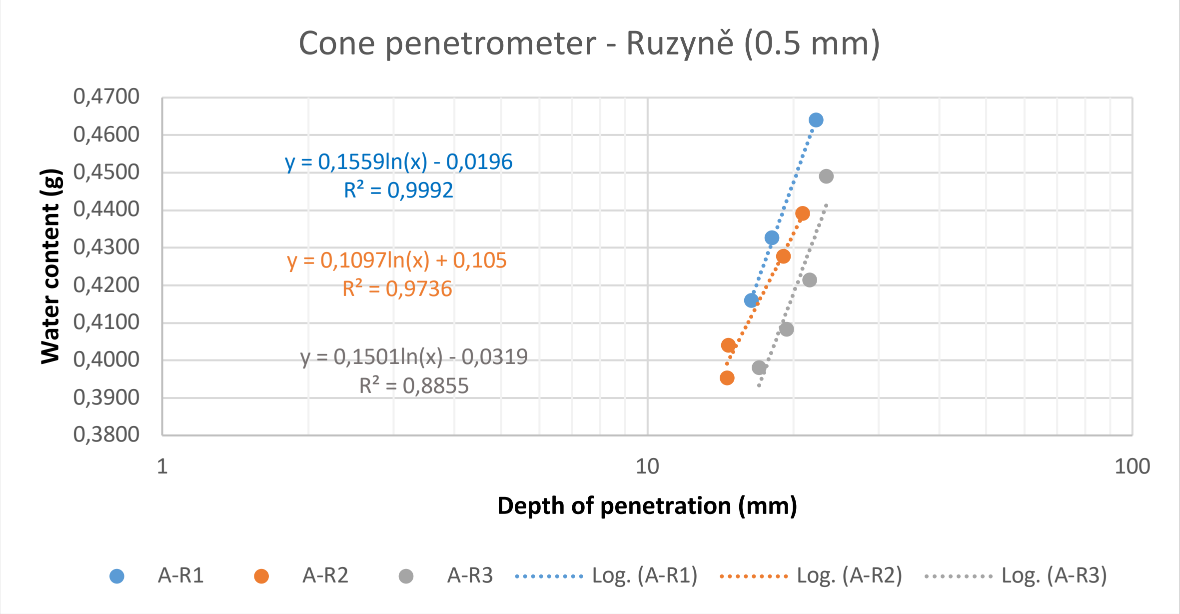
Results, presented in the Table 9, show that Ruzyně soil has highest liquid limit obtained by Casagrande apparatus, while Uhříněves soil has the lowest liquid limit values.

Table 9: Liquid limits obtained by Casagrande apparatus for all three localities and sieves with 0.4- and 0.5-mm diameters.

Locality	Sample	Sieve (mm)	Liquid limit (%)	Average liquid limit (%)
Ruzyně	A-R1	0.5	40.97	40.37
	A-R2		39.74	
	A-R3		40.41	
	A-R4	0.4	40.08	40.02
	A-R5		40.00	
	A-R6		39.98	
Suchdol	A-S1	0.5	33.89	35.28
	A-S2		35.77	
	A-S3		36.19	
	A-S4	0.4	35.55	35.39
	A-S5		35.25	
	A-S6		35.37	
Uhříněves	A-U1	0.5	31.01	30.99
	A-U2		31.15	
	A-U3		30.83	
	A-U4	0.4	30.97	31.03
	A-U5		31.16	
	A-U6		30.98	

5.5.2. Cone penetrometer

Liquid limit graphs obtained by cone penetrometer are presented in Figures 29, 30 and 31.



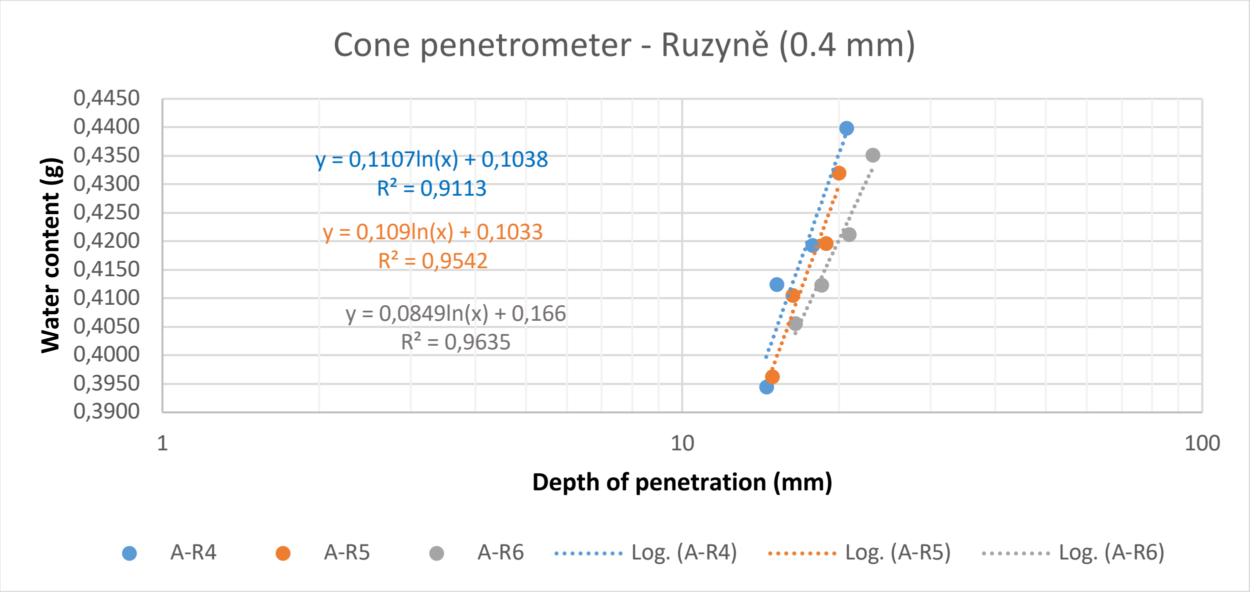
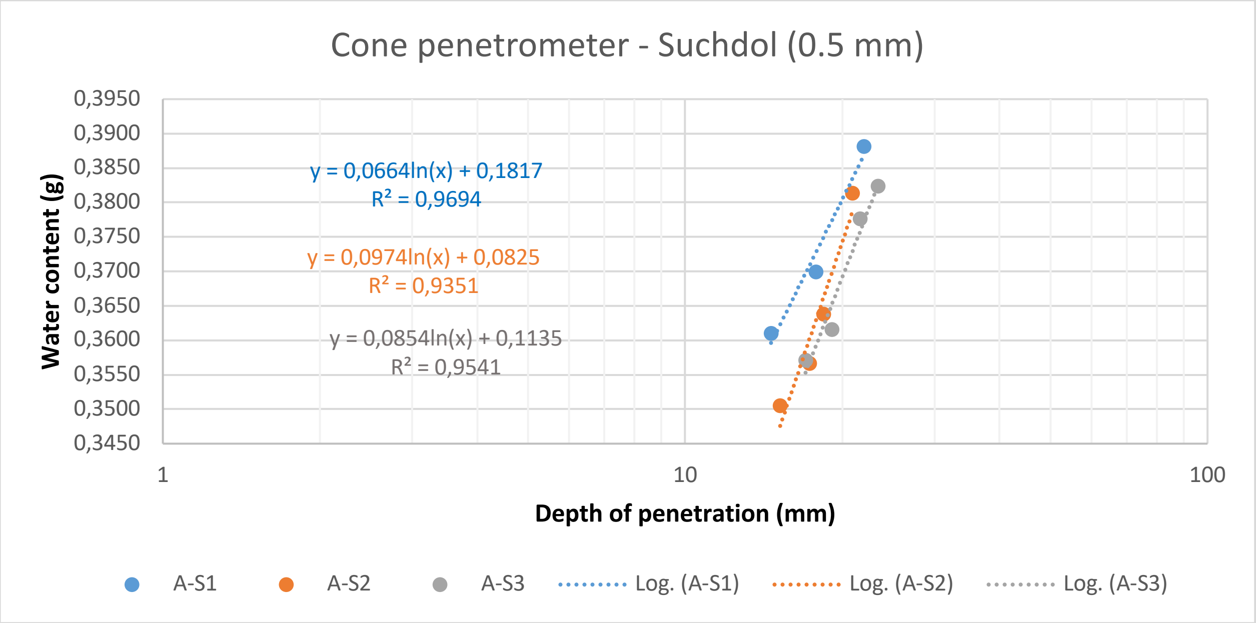


Figure 29: Liquid limit graphs by cone penetrometer for Ruzyně soil, using 0.4 mm diameter sieve (A-R1, A-R2 and A-R3) and 0.5 mm diameter sieve (A-R4, A-R5 and A-R6).



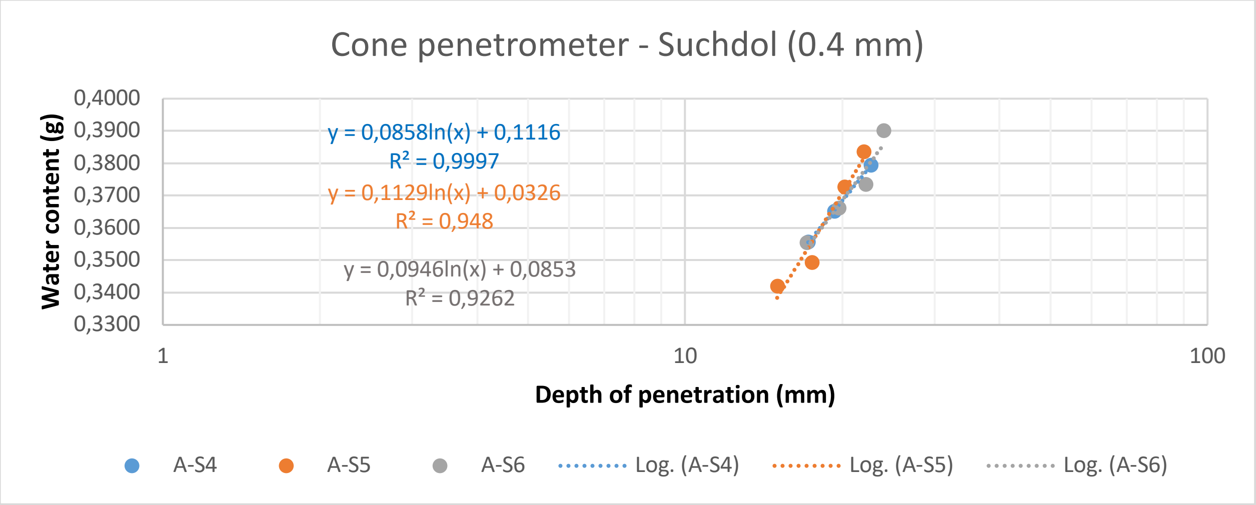
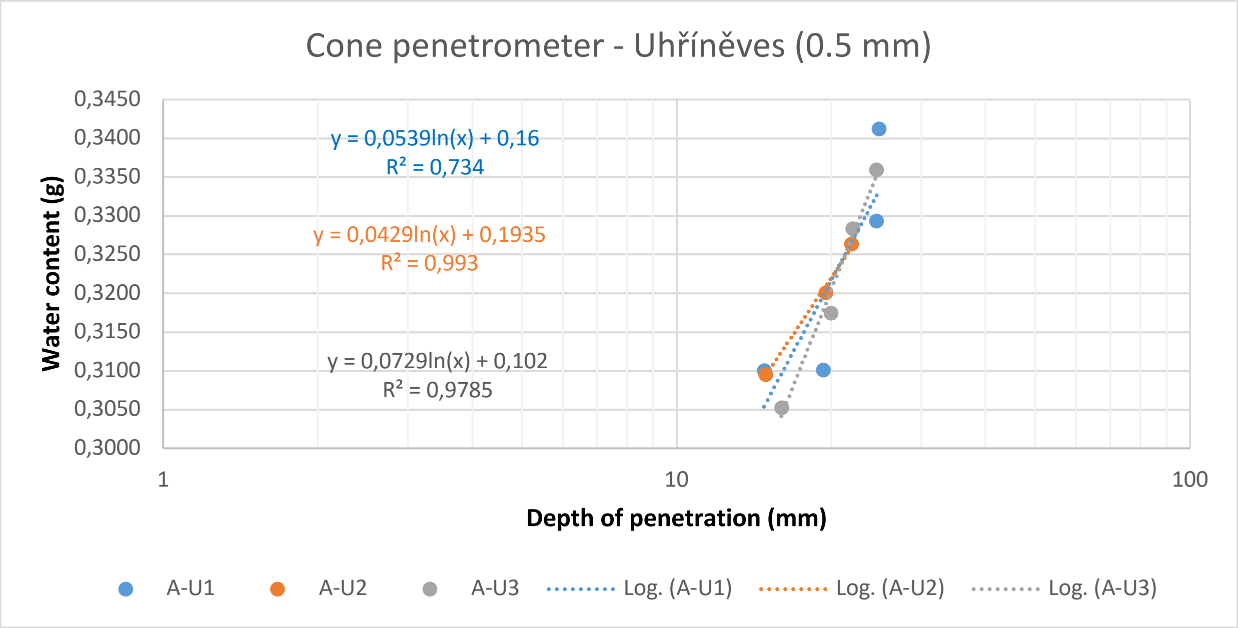


Figure 30: Liquid limit graphs by cone penetrometer for Suchdol soil, using 0.4 mm diameter sieve (A-S1, A-S2 and A-S3) and 0.5 mm diameter sieve (A-S4, A-S5 and A-S6).



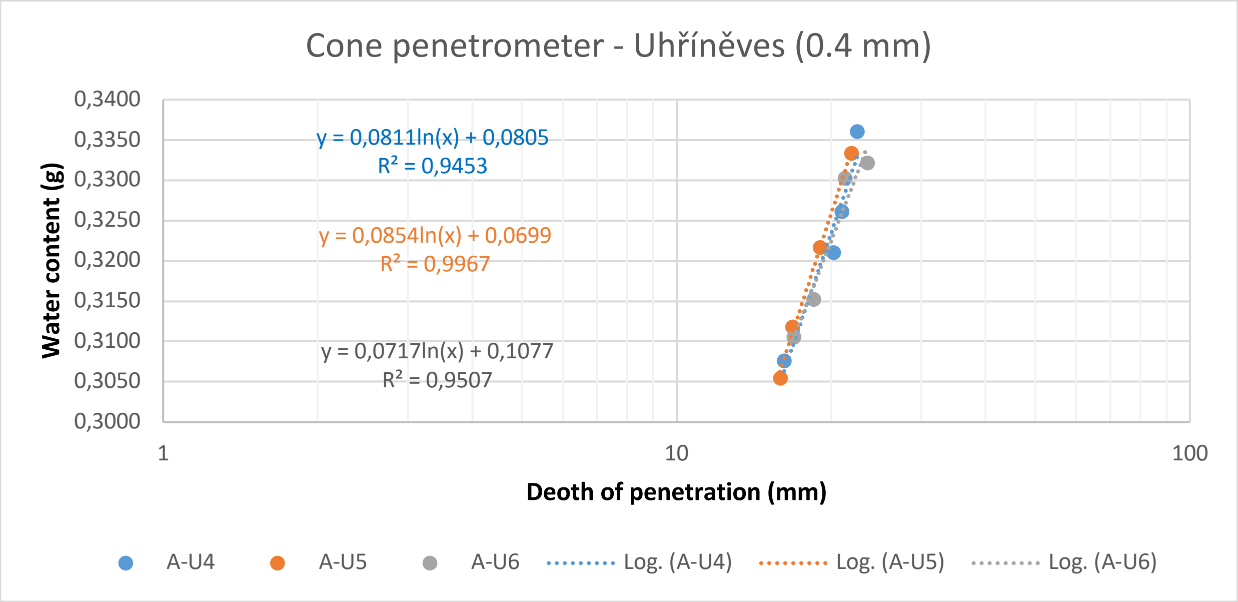


Figure 31: Liquid limit graphs by cone penetrometer for Uhříněves soil, using 0.4 mm diameter sieve (A-U1, A-U2 and A-U3) and 0.5 mm diameter sieve (A-U4, A-U5 and A-U6).

Results, presented in the Table 10, show that Ruzyně soil has highest liquid limit obtained by cone penetrometer, while Uhříněves soil has the lowest liquid limit values.

Table 10: Liquid limits obtained by cone penetrometer for all three localities and sieves with 0.4- and 0.5-mm diameters.

Locality	Sample	Sieve (mm)	Liquid limit (%)	Average liquid limit (%)
Ruzyně	A-R1	0.5	44.74	43.29
	A-R2		43.36	
	A-R3		41.78	
	A-R4	0.4	43.54	42.85
	A-R5		42.98	
	A-R6		42.03	
Suchdol	A-S1	0.5	38.06	37.47
	A-S2		37.43	
	A-S3		36.93	
	A-S4	0.4	38.78	37.58
	A-S5		37.08	
	A-S6		36.87	
Uhříněves	A-U1	0.5	32.15	32.13
	A-U2		32.20	
	A-U3		32.04	
	A-U4	0.4	32.35	32.39
	A-U5		32.57	
	A-U6		32.25	

5.5.3. Casagrande apparatus and cone penetrometer comparison

In order to compare these two methods, average values were taken for both methods and all three localities. Also, standard deviation and CV values were calculated. Presented results, summarized in the Table 11, indicate that Uhříněves soil has the smallest standard deviation and coefficient of variation values for both methods. Ruzyně showed smaller standard deviation and CV values with Casagrande apparatus, while Suchdol soil gave smallest standard deviation and CV values with cone penetrometer. Very small variation shows on good quality of the measurements, which is extremely important for the liquid limit determination. Cone penetrometer gave systematically higher values than the Casagrande apparatus. The absolute difference varies according to the locality.

Table 11: Comparison between Casagrande apparatus and cone penetrometer, considering difference in standard deviation and coefficient of variation values.

Locality	Method	Average liquid limit (%)	Difference in average liquid limit (%)	Standard deviation (%)	CV (%)
Ruzyně	Casagrande apparatus	40.20	2.88	0.40	1.0
	Cone penetrometer	43.07		0.99	2.3
Suchdol	Casagrande apparatus	35.33	2.19	0.72	2.0
	Cone penetrometer	37.53		0.69	1.8
Uhříněves	Casagrande apparatus	31.02	1.24	0.12	0.4
	Cone penetrometer	32.26		0.17	0.5

When the two methods are compared statistically (One-way ANOVA), there is no significant difference ($p > 0.05$), see Figure 32.

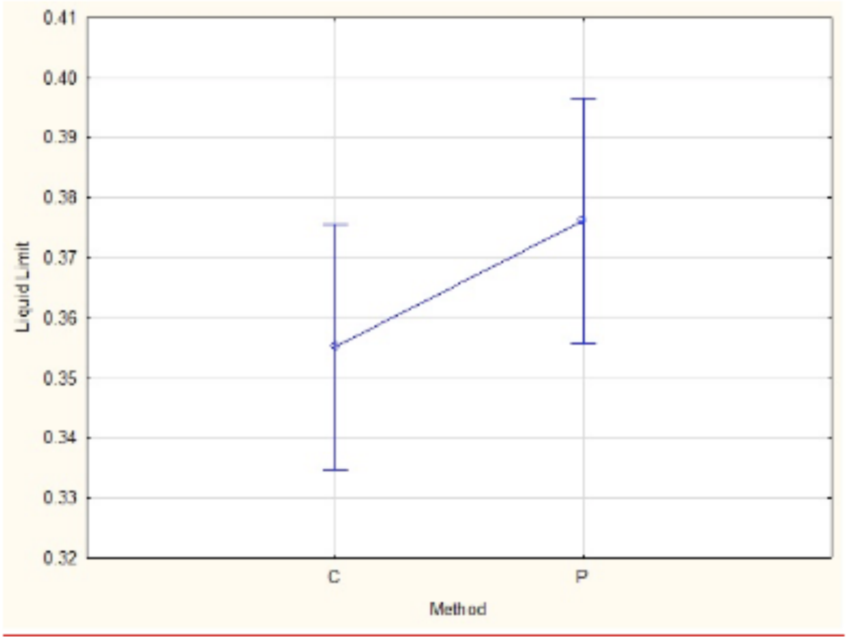


Figure 32: Comparison between the two methods for liquid limit determination (C denotes Casagrande apparatus, P denotes cone penetrometer).

Significant differences ($p < 0.05$) were found in the values obtained from the three localities, regardless the method, see Figure 33.

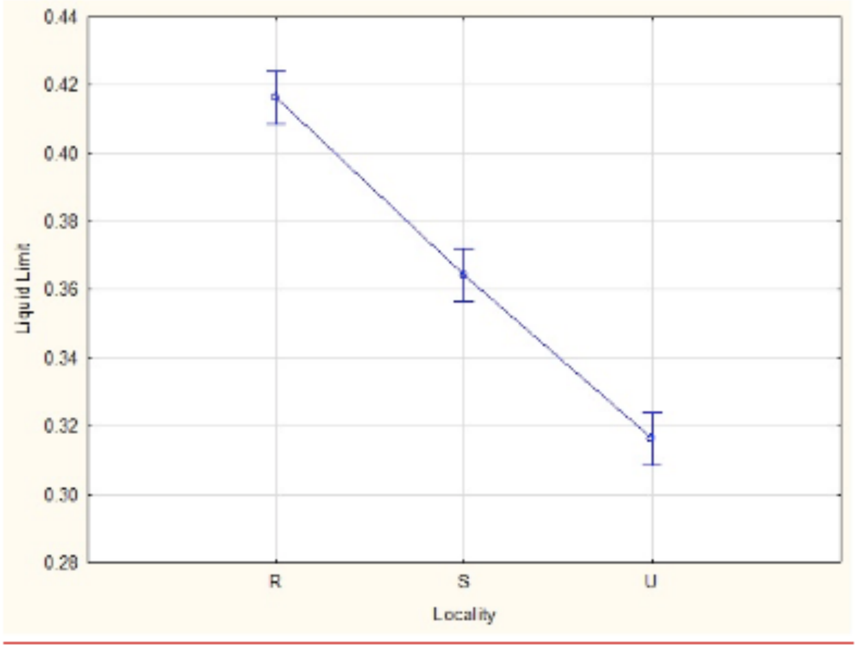


Figure 33: Comparison of liquid limits from different localities (R – Ruzyně, S – Suchdol, U – Uhříněves).

However, multivariate Wilks test carried out for the combined effect of the method and locality shows, that the method used has significant effect on the resulting liquid limit value ($p < 0.5$, see Figure 34).

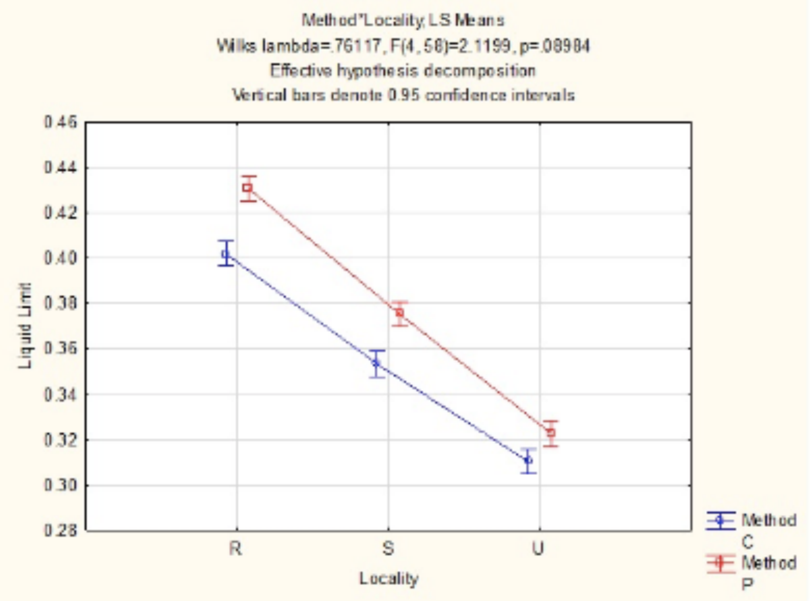


Figure 34: Comparison of combined effect of method (C – Casagrande apparatus, P – cone penetrometer) and locality (R – Ruzyně, S – Suchdol, U – Uhříněves) on the value of liquid limit.

When considering the sieve of the sieve, it has no significant difference ($p > 0.05$; see Figure 35), regardless either the method (Figure 36), or the locality (Figure 37).

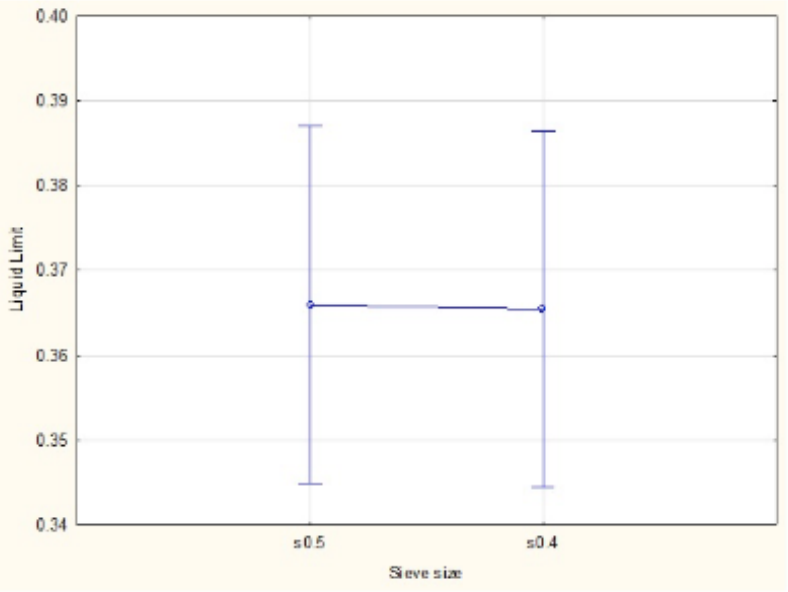


Figure 35: Comparison of the effect of the sieve's size.

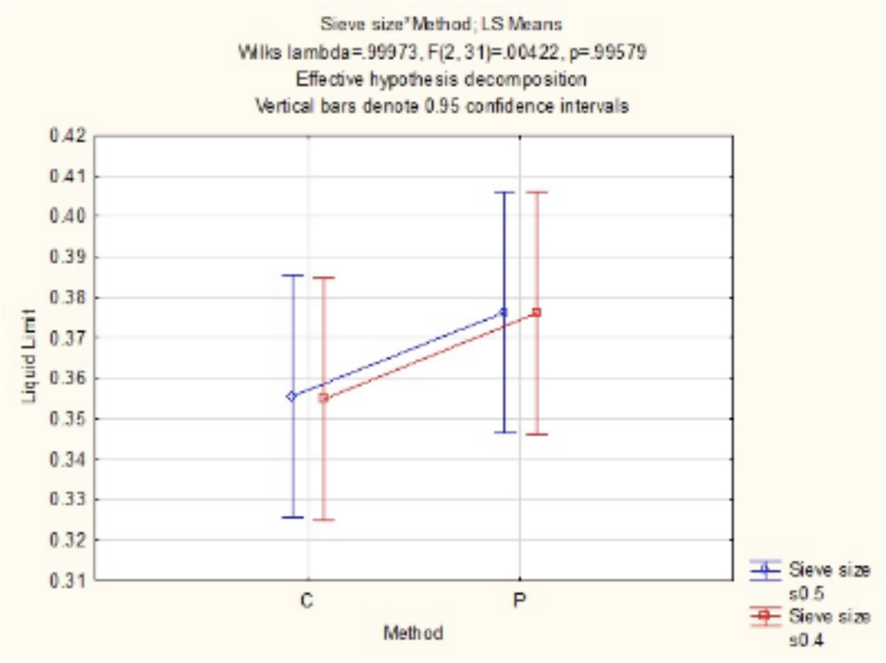


Figure 36: Multivariate test of significance combining the effect of method and size of the sieve.

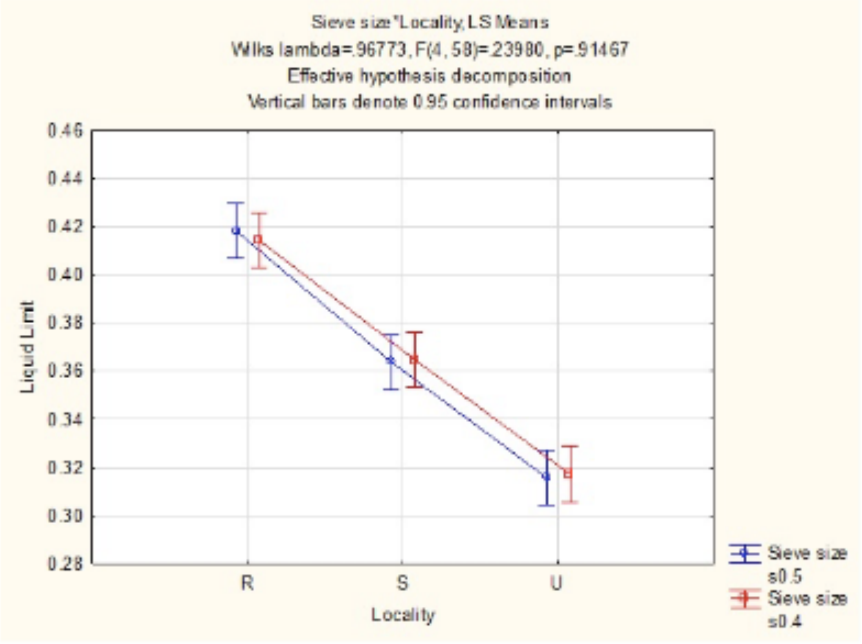


Figure 37: Multivariate test of the significance combining the effect of locality and size of the sieve.

5.6. Index of plasticity calculation

From the obtained values of plastic and liquid limits, the index of plasticity was calculated separately for both methods (see Figure 38). Localities Suchdol and Uhříněves are medium plastic soils, while Ruzyně locality belongs to the highly plastic soil. The method in this case did not influence the classification, however, the difference almost 3% could be determinant in other cases. ANOVA of main effects (Figure 39) indicated on the level $p < 0.5$ that the method used for determination of LL has significant effect on the resulting IP value.

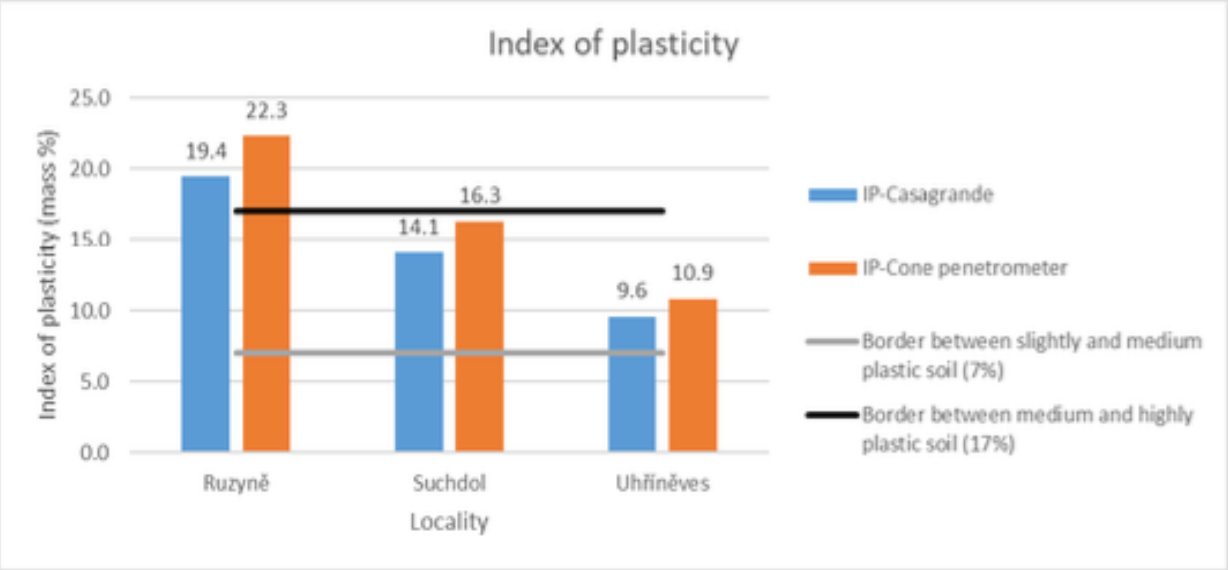


Figure 38: Index of plasticity calculated from plastic limit and liquid limit obtained by both methods.

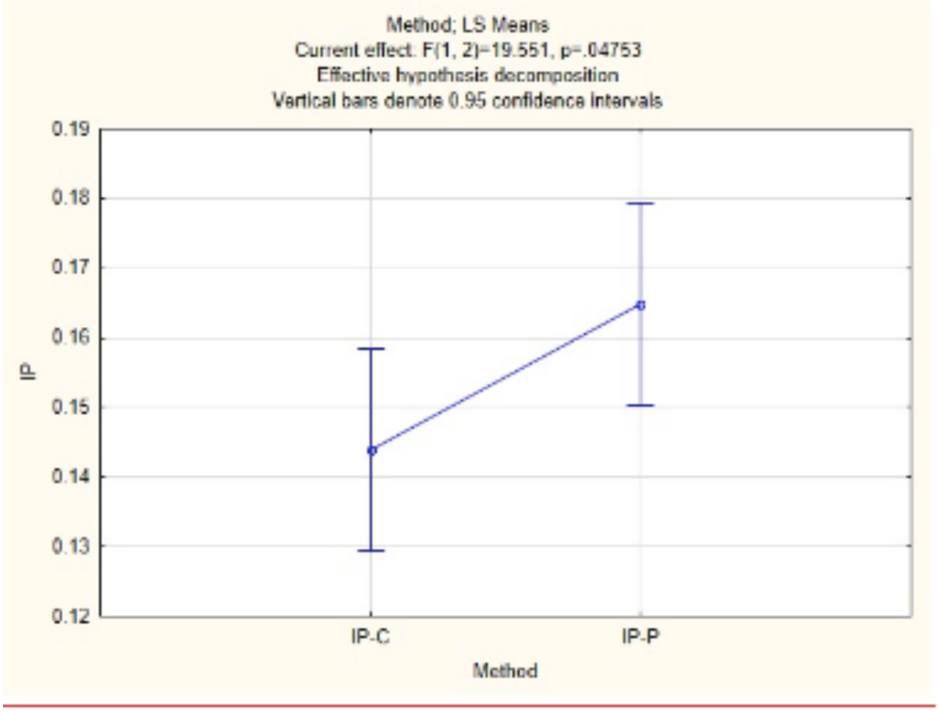


Figure 39: Univariate test of significance showing the effect of the used LL method on IP value.

6. Discussion

After detailed descriptions of methods and analytical measurements performed, as well as outlining results obtained from the experiments, this section considers some of the most important findings relevant to the hypothesis and aims of the thesis, which have been defined at the beginning of this thesis.

Soil characterization analyses (particle density, particle size distribution, pH and electrical conductivity) have been performed in order to get more data about the soil samples from three different localities: Ruzyně, Suchdol and Uhříněves. These results are important, as literature implies that there is strong correlation between all these parameters and Atterberg's limits. Polidori (2007) argues that dynamic factors, such as pH, temperature, cation exchange capacity, type and quantity of cations present in the soil solution, are constantly changing due to human effect through alteration of environment. Some of their impacts can be seen in acid rain phenomenon or use of chemical fertilizers and pesticides for agricultural purposes.

The common range of particle density in soils is between 2.55 and 2.75 g/cm^3. After analysis of particle density, it has been concluded that Suchdol sample has slightly lowest density (≈ 2.61 g/cm^3), while Uhříněves has highest value (≈ 2.70 g/cm^3). Generally, loose, well-aggregated, porous soils and those rich in organic matter have lower bulk density. Suchdol soil is example of Chernozem soil, which are one of the most fertile soils, which explains its lowest particle density, compared to other two localities. All three soils were in the range of particle density of soils, which suggests that there have been no mistakes in the experiments.

However, even though Suchdol soil had highest organic matter, it had the most alkaline pH (7.80) from the three localities, while Uhříněves soil was the most acidic (pH 6.74) soil and Ruzyně was the most neutral (pH 7.72) one. Due to the fact that Suchdol soil has the most basic pH, it had the highest electrical conductivity values (223 µS/cm), while Uhříněves soil, being the most acidic one, had the lowest electrical conductivity values (180 µS/cm). Low values of EC indicate no effect on Atterberg's limits.

Even though there have been slight differences between the localities in terms of particle density, pH and electrical conductivity, particle size distribution analysis has identified that all three localities belong to the same soil texture class – silt loam. Additionally, all three localities showed that they have highest percentage of silt and lowest amount of clay in their texture. Atterberg's limits can vary between expandable (such as montmorillonite) and non-expandable (such as kaolinite and illite) minerals, which is why their contents need to be known before determination of LL and PL values (Dolinar, 2007). In future research, mineralogical composition of soils should be determined, especially for soils which have higher clay content, as clay minerals can affect liquid limit.

After soil characterization analyses, plastic and liquid limits have been determined. With plastic limit analyses, it has been determined that Ruzyně soil had lowest average water content from all three localities. Furthermore, Ruzyně soil had highest standard deviation and CV values, which can be attributed to the fact that there have been some mistakes during the experiment, which affected overall calculations and results. According to standard procedure CEN ISO/TS 17892-12, the plastic limit should be determined from two repetitions, which do not differ more than 0.5% difference by mass. Within the thesis, 10 repetitions were performed in order to test the overall variability of the method and consistency of the operator. The absolute range of the obtained values varied from 0.8% to 2.3% by mass. As Ruzyně soil has been the first soil to experiment with, operator did not have sufficient training and experience, which might be the reason for higher variability.

For liquid limit determination, comparison between Casagrande apparatus and cone penetrometer needed to be made. The first conclusion which can be drawn is that for all samples, LL values were always slightly higher for fall cone penetrometer measurements. Nonetheless, these values never showed large difference in results, which supports findings by Hrubesova et al. (2016), where it was concluded that results between the two methods are very similar. In this thesis, for the first method, Casagrande apparatus, it has been discovered that Ruzyně soil has highest (40.20%), while Uhříněves soil has the lowest liquid limit values (31.02%). Consistent results have been obtained by cone penetrometer, which indicated the reliability of experiments and calculations. With this method, it has been confirmed that Uhříněves soil had the lowest liquid limit values (32.06%), while highest ones have been observed in Ruzyně soil (43.07%). Fojtova et al. (2009) analyzed 52 samples with LL values varying between 21.49 to 49.56% for Casagrande cup, while LL values for cone penetrometer were in range 24.11-51.83%. These results are in accordance with results presented in this thesis; results are in the similar range and LL values obtained by fall cone penetrometer were higher than those obtained by Casagrande apparatus. Additionally, statistical analysis in terms of average values, standard deviation and coefficient of variation (CV) has been conducted. With such investigation, it has been determined that Uhříněves soil has the smallest standard deviation and coefficient of variation values for both methods. Ruzyně showed smaller standard deviation and CV values with Casagrande apparatus, while Suchdol soil gave smallest standard deviation and CV values with cone penetrometer. The smallest difference between the two methods was measured in Uhříněves soil samples (1.24%) and it can be attributed to the fact that it was the last soil to be analyzed. By that point, operator has been trained sufficiently in order to produce the most reliable results. On the other hand, highest difference between two instruments was observed in Ruzyně samples (2.88%). Experiments conducted by Fojtova et al. (2009) showed differences between these two methods in range between 1.19 and 3.91%. LL values determined by the cone penetrometer were about 1% higher than Casagrande apparatus values in experiments conducted by Spagnoli (2012). This difference was slightly higher than the one observed by Di Matteo (2012), where difference of LL values was 2-3%. The authors did not accept samples which have differences higher than 4%, as it was suggested that experiments with these samples should be repeated for both instruments. Results presented in this thesis show no samples with difference higher than 4%, which indicate that current experiments should not be repeated.

The difference of liquid limits between sieves with diameters of 0.4 and 0.5 mm has also been observed both for Casagrande cup (see Table 8) and cone penetrometer (see Table 9). It has been proved that there is no statistical difference between samples sieved on these two different sieves. Consistently with above mentioned results, Casagrande apparatus gave results with lower difference of LL values between two sieves; the difference between values varied between 0.04 and 0.35%. On the other hand, difference between two sieves for cone penetrometer was present in range from 0.11 to 0.44%. However, this difference is still less than 1% and it can be concluded that it is negligible and different sieve diameters had no significant statistical effect on calculation of liquid limit between the two analytical instruments.

Not all types of soils are suitable only for one laboratory method for testing of Atterberg's limits. As previously mentioned, clays minerals can affect the liquid limit values, which might be differ between the two analytical methods. Experiments conducted by Niazi et al. (2019) and Hrubesova et al. (2016) suggest that cone penetrometer gives lower LL values than Casagrande cup for high plasticity soils. Conversely, cone penetrometer will yield higher values for low plasticity soils, compared to Casagrande cup. Such conclusion could not be drawn in this thesis because cone penetrometer always gave slightly higher values than Casagrande apparatus. For future research, samples with different plasticity should be used, in order compare the two methods and support conclusions obtained by other authors.

During LL detetmination, some outliers occurred and and hence those samples were excluded from the calculation. It did not affect the results, as always 4 samples were used for regression, thus 3 samples were sufficient after excluding the outliers. In total, 7 outliers were excluded from the total 36 LL, 3 from Casagrande apparatus and 4 from the cone penetrometer, mostly in Suchdol samples (4). These errors are generally equally distributed between the methods.

Besides errors which occurred during experiments, temperature had effect on soil samples and therefore results were impacted, too. For liquid limit determination and comparation between Casagrande apparatus and cone penetrometer, temperature has been different during the first days of experiment, compared to the other ones. Such higher temperature contributed to the faster drying of the sample and evaporation of the water inside it, which might have affected the number of outliers.

7. Conclusions

Results have shown that there is slight difference between the two methods – Casagrande cup and cone penetrometer. However, it can be concluded that Casagrande apparatus produced slightly better results for two, out of three localities, in terms of standard deviation and coefficient of variation. Difference between the two methods ranged from 1.24 to 2.88%, which agrees with results obtained in the literature, whose results range between 1 and 4%. Furthermore, cone penetrometer yielded higher LL values compared to the Casagrande cup. Similar results were acquired by other authors and hypothesis presented at the beginning of this research work has been supported.

Nonetheless, it has to be stressed that the differences presented in this work were small, which suggests that more samples need to be taken and broader study needs to take place. For future work, it can be suggested to conduct mineralogical composition analysis, as clay minerals can interfere with the Atterberg's limits, especially liquid limit values. Additionally, different types of soils, with different plasticities, will yield different results by these two methods. As literature and previous experiments have shown, cone penetrometer will give lower LL values than Casagrande cup for high plasticity soils, while the opposite is true for low plasticity soils. This is why soils with different plasticities should be used in experimental method, for better comparation between the two methods.

For future experiments, inclusion of two operators can be advised, in order to eliminate the possibility of drying out the sample, especially during summertime and higher temperatures in general. One operator could be technician – in charge of cleaning the equipment, while the operator performs the experiment. However, it is of crucial importance that only one operator constantly makes decision during experiments, especially for Casagrande apparatus, as it is more subjective than the cone penetrometer, and different operators can draw different conclusions, which will ultimately lead to difference in results. Besides this, future studies on Atterberg's limits should include more samples, especially from different localities. The samples presented in this paper were all from Prague, some even in close proximity from each other. This made it more difficult to draw more precise conclusions. Broader study, which would involve samples from different parts of Czech Republic, with different soil texture and especially clay content would be of higher importance, as it would be interesting to see how soils with different textures and clay content behave while performing Atterberg's limits experiments. In the end, wider statistical analysis with more parameters should have been done in order to obtain more results ready for interpretation.

When it comes to personal experience, what should definitely be mentioned is that it was easier to track the progress with Casagrande cup, because there was always the exact range for precise results. However, it was easier to work with the cone penetrometer because it could withstand more liquid soils. Additionally, sometimes during the experiments, it was more difficult to cut the ideal groove with Casagrande cup, as even the slight mistake while cutting the groove removed the smoothened soil particles from the surface of the cone. This is why experiments needed to be repeated a lot more often with Casagrande cup than with cone penetrometer. To summarize, it was a lot more comfortable to work with the cone penetrometer, mostly because the results were straightforward and did not rely on subjective opinion from operators' side. For more experienced operators, Casagrande apparatus would be more pleasant method, but for those operators with less training, cone penetrometer is safer method to work with, in order to eliminate any possibility of mistakes.

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