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Original Scientific Paper

COMPARATIVE ANALYSIS OF ATTERBERG'S LIMITS OF FINE-GRAINED SOIL DETERMINED BY VARIOUS METHODS

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Abstract. *Determination of the Atterberg's limits is necessary for the classification of fine-grained soil. That limits can be determined according to the valid standard SRPS EN ISO 17892-12. Two methods are prescribed by the standard for determining the liquid limit: the Casagrande cup and the Fall Cone test, and one method for determining the plasticity limit: the thread-rolling method. In this paper the Fall Cone method was also used as an alternative method to determine the plastic limit. Ten samples of various fine-grained materials, originating from the wider area of the city of Niš, were tested. The classification of all samples was performed based on the results obtained by the methods prescribed by the standard and alternative methods. Comparative analysis shows that the results obtained by applying standard and alternative methods are close, but also that the scattering of results obtained by the Fall Cone method is significantly less, whereas the reproducibility is higher.*

Key words: *fine-grained soil, liquid limit, plastic limit, plasticity index, Fall Cone method*

1. Introduction

The Atterberg's limits (Liquid Limit LL, Plastic Limit PL, Shrinkage Limit SL) are related to the amount of water attracted to the surface of the soil particles and are predominant factors for identifying and classifying a fine-grained soil. The cohesive soil can be in various physical states, i.e. of different consistency (solid, semi-solid, plastic, liquid) (Fig. 1).

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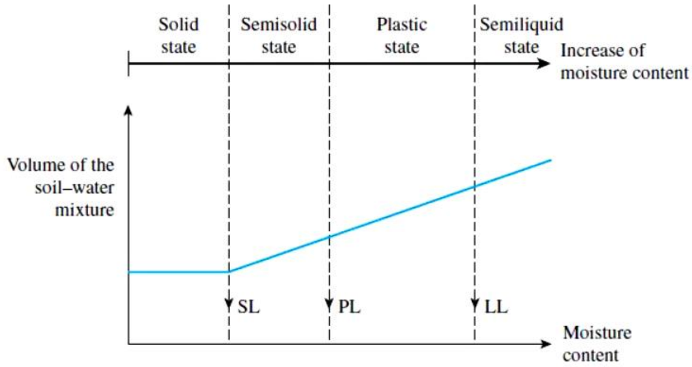

Fig. 1. Diagram of soil consistency

In nature, the soil often occurs in a plastic state. Plasticity Index (PI) represents the difference between the Liquid Limit and Plastic Limit (PI = LL - PL). The LL value, which may vary over a wide range, is used in the classification and preliminary evaluation of fine-grained soils in engineering works. If the LL is incorrectly defined, it can lead to the rejection of satisfactory materials, even the acceptance of unsuitable materials [1]. To determine LL two methods can be used according to SRPS EN ISO 17892-12 [2]: the Casagrande method and the Fall Cone method. The Fall Cone method, on the other hand, is easier, faster and less sensitive to the subjective factors (better repeatability of the test) and from this point of view this method was accepted as a standard method for LL determination in the European Standard EC7 [3]. A number of studies have been dealing with comparing the results obtained by applying these two methods [4–10]. Unlike the liquid limit, the plastic limit test is prescribed in a unique way – thread-rolling method. This paper presents an analysis of the results obtained using the standard and alternative method for PL determination proposed by Wood and Wroth [11]. Despite its wide use, thread-rolling method is often criticized for the influence of the assessment by the laboratory technician during the applying of the method as well as insufficiently good results for sandy clays. According to Whyte [12] when applying the standard method, the result is affected by several factors: the pressure applied to the soil thread; the geometry, i.e. the contact area between hand and thread; the friction between the soil, hand and base plate; the rate of rolling. None of these variables is controlled easily, and consequently the standard plastic limit test does not provide a direct measurement of soil strength. A modified Fall Cone method, proposed by Wood and Wroth [11] using a heavier cone, is very current. It differs from the standard cone for determining the liquid limit in the weight and the angle of the cone (cone characteristics: apex angle 60°, weight 240 g). The advantages and disadvantages of methods for testing the Atterberg limits using Fall Cone method are presented in the case studies [12,13].

The necessary values for the classification of materials were obtained in two ways in this paper. Namely, first the liquid limit was obtained using two methods prescribed by the standard, and then the plasticity limit was obtained using two methods (one method prescribed by the standard, the other alternative). The classification was performed in two ways: (1) using Casagrande cup and thread-rolling method, and (2) using the Fall Cone method. The obtained results are compared and their dependence is shown.

2. MATERIALS AND EXPERIMENTAL METHODS

As part of the research presented in this paper, 10 samples (S1–S10) were tested in order to determine the liquid limit and the plastic limit. The soil samples used in this analysis were taken from different places within the wider area of the city of Niš (Fig. 2). The samples are fine-grained materials that are typical for this area. Table 1 contains the labels of all samples, the locations from which they originate, the description of the sample material and the laboratory-determined values of specific gravity (Gs).

Table 1 Samples used for testing

Sample	Origin	Description	G_s [1]
S1	Babin Kal–Bela Palanka	Crushed stone (fine-grained fractions)	2.650
S2	Ličje–Gadžin Han	Crushed stone (fine-grained fractions)	2.666
S3	Doljevac 1	Sandy clay	2.648
S4	Aleksinac 1	Light brown clay	2.639
S5	Doljevac 2	Light brown clay	2.642
S6	Bancarevo 1	Brown clay	2.635
S7	Aleksinac 2	Sandy clay	2.634
S8	Bancarevo 2	Brown clay	2.630
S9	Ostrovica 1	Light brown clay	2.624
S10	Ostrovica 2	Brown clay	2.619

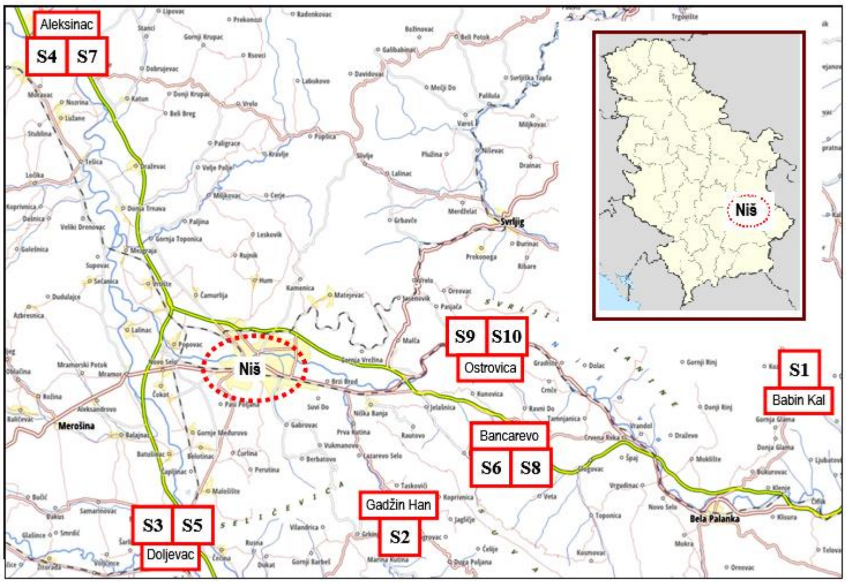

Fig. 2 Sample labels and locations in the wider area of the city of Niš where they were taken

For each sample the liquid limit was determined using two different procedures - the Casagrande method (results labeled LL_{cup}) and the Fall Cone method (results labeled LL_{cone}). For each sample, the Plastic Limit was determined using 2 different procedures -

the thread-rolling method (results marked by $PL_{rolling}$) and the Modified Fall Cone method (results marked PL_{cone}).

The obtained results were compared and discussed. Based on the comparative analysis, the relationship between LL_{cone} and LL_{cup} values, and then $PL_{rolling}$ and PL_{cone} which is relevant for fine-grained soils from this area, should be defined by mathematical expression.

According to SRPS EN ISO 17892-12, each sample of soil material is sieved through a 0.5 mm sieve to remove larger particles. The sample is then mixed with distilled water and homogenized with metal blades, with the aim that the whole sample has the same moisture content. Each sample was tested 10 times. For all samples, the classification was performed on the plasticity diagram, based on the obtained values LL_{cup}–$PL_{rolling}$, LL_{cone}–PL_{cone}.

2.1. Determination of Liquid Limit

The Casagrande method uses a cup, within which a soil paste is placed, then the soil is split by cutting a groove and also the cup is drop on a base. The Liquid Limit, according to this method, is the water content of the soil determined for a number of 25 blows (Fig. 3).

The cone penetrometer technique uses a free falling cone (cone characteristics: apex angle 30°, weight 80 g) and is based on the relation between water content and cone penetration depth (Fig. 3). Considering this method, the Liquid Limit represents the water content equivalent to cone penetration depth of 20 mm.

2.2. Determination of Plastic Limit

The standard SRPS EN ISO 17892-12 for determining the plastic limit implies manual making of rollers on a glass plate (Fig. 3). The plastic limit represents the water content at which the roller with a thickness (diameter) of 3.0 mm is cracked. It has been shown that the values obtained by this method depend to a great extent on the assessment of the operator. Sherwood [4] came to the conclusion after a large number of tests that variations of the obtained results may be up to 12% for the same soil sample treated by several operators. The Modified Fall Cone method (cone characteristics: apex angle 60°, weight 240 g) can be considered as more reliable. Plastic Limit represents the water content equivalent to cone penetration depth of 20 mm. Although this method is not yet included in the standard, it has been proven to be very successful in numerous research [14–17]. By using this method, the influence of the laboratory technician on the obtained results is reduced, and thus, it is expected that the results will be much closer to each other than the results obtained by the thread-rolling method.

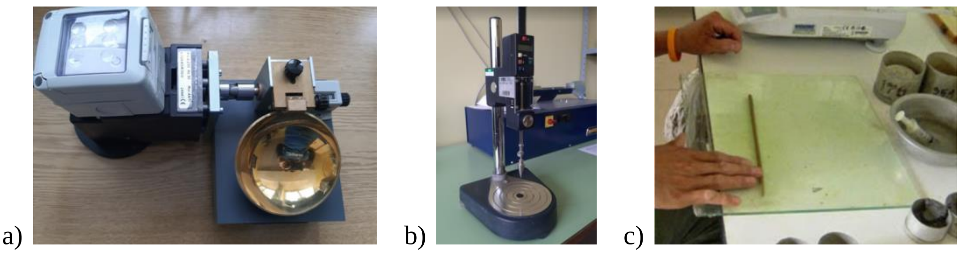

Fig. 3. Equipment for determination of Liquid Limit and Plastic Limit: a) Casagrande cup; b) Falling cone (penetrometer); c) thread-rolling method

3. RESULTS AND DISCUSSION

The correlations proposed by the authors based on the study of local fine-grained materials are numerous and different mathematical complexities, from simple linear equations to higher order equations. Some of the correlations can be seen in the Table 2. In the equations, LL_{cone} is Liquid Limit determined by Fall Cone method and LL_{cup} is Liquid Limit determined by Casagrande method.

Table 2 Equations correlating the LL values obtained by using the fall-cone apparatus and the Casagrande cup [18]

Author (Year)	Number of samples	LL range (%)	Correlation	R^2
Sherwood and Ryley (1970)	25	30–72	$LL_{CONE} = 0.94 \cdot LL_{CUP} + 0.97$	-
Leroueil and Le Bihan (1996)	43	30–74	$LL_{CONE} = 0.86 \cdot LL_{CUP} + 6.34$	-
Feng (2001)	66	25–76	$LL_{CONE} = 0.94 \cdot LL_{CUP} + 2.60$	-
Dragoni et al. (2008)	41	27–74	$LL_{CONE} = 1.02 \cdot LL_{CUP} + 2.87$	0.980
Fojtova et al. (2009)	52	20–51	$LL_{CONE} = 1.00 \cdot LL_{CUP} + 2.44$	0.978
Di Matteo (2011)	6	20–40	$LL_{CONE} = 1.00 \cdot LL_{CUP} + 2.20$	0.980
Spagnoli (2012)	50	20–61	$LL_{CONE} = 0.99 \cdot LL_{CUP} + 2.44$	0.990
Silva (2013)	10	38–45	$LL_{CONE} = 1.05\ LL_{CUP} + 0.61$	0.978
El-Shinawi (2017)	40	28–70	$LL_{CONE} = 0.91 \cdot LL_{CUP} + 5.64$	0.949
Niazi et al. (2019)	65	11–65	$LL_{CONE} = 0.89 \cdot LL_{CUP} + 4.20$	0.985

The obtained values of LL and PL are shown in Table 3 and Table 4. Table 3 shows the values obtained by the Casagrande method (LL_{cup}) and by the Fall Cone method (LL_{cone}), and Table 4 shows the values obtained by the thread-rolling method ($PL_{rolling}$) and the Fall Cone method (PL_{cone}). Tables show the obtained results of the minimum and maximum values, their difference, as well as the mean value of LL and PL. For each tested sample, the standard deviation (S.D.) and the coefficient of variation (C.O.V.) of the obtained results were calculated. These statistical parameters better express the scattering of results and reproducibility. C.O.V. value is represented by default as a dimensionless quantity, but in the given tables, for the sake of a simpler comparison, the value is shown in percent.

It can be seen that LL values ranging from 16.56% to 49.74%, which is in accordance with the results of the tests performed so far on materials from this area (Table 3). For LL values less than 40%, a strong linear dependence and almost coincidence with the 45° line can be observed. Other authors have shown similar results in their research [5-10]. The obtained PL values are in the range from 11.37% to 30.50%. It is obvious that for all samples the scattering of the results is higher when the Casagrande cup and thread-rolling method were used. The differences in the liquid and plastic limits results obtained by Casagrande cup and thread-rolling, considering all samples, are greater than 2%. S.D. values for the Casagrande cup (0.84% to 1.74%) and thread-rolling method (0.78% to 1.35%) are significantly higher than for the Fall Cone method: LL (0.51% to 1.31%) and PL (0.62% to 1.24%). Similarly, C.O.V. values for thread-rolling method (3.74% to 6.31%) are significantly higher than for Fall Cone method (2.30% to 4.96%). Based on the fact that for all tested samples the values of S.D. and C.O.V. are significantly lower when using the Fall Cone method, it can be concluded that more reproducible results are obtained with this method. In addition, it was shown that the mean value of the plastic limit for all samples is slightly higher when using the Fall Cone method.

Table 3 LL values determined by the Casagrande method and the Fall Cone method

		LL (%)									
	Sample	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
LL_{cup}	LL_{max} (%)	17.97	28.42	32.45	34.09	36.86	38.16	41.23	44.56	46.72	49.56
	LL_{min} (%)	15.94	26.03	30.36	30.38	34.23	35.44	38.90	40.74	42.66	45.32
	ΔLL (%)	2.03	2.39	2.09	3.68	2.63	2.72	2.33	3.82	4.06	4.24
	LL_{mean} (%)	16.56	26.98	31.64	31.56	36.07	36.66	40.31	42.17	44.35	46.51
	S.D. (%)	0.84	1.23	0.98	1.25	1.16	1.22	1.42	1.37	1.63	1.74
	C.O.V. (%)	5.07	4.56	3.10	3.96	3.22	3.33	3.52	3.25	3.76	3.74
LL_{cone}	LL_{max} (%)	17.62	28.77	32.11	33.94	36.95	38.34	42.64	46.05	48.11	52.35
	LL_{min} (%)	16.03	26.85	29.76	29,85	33,81	35.57	40.88	42.67	45.19	48.34
	ΔLL (%)	1.59	1.92	2.35	4.09	3.14	2.77	1.76	3.38	2.92	4.01
	LL_{mean} (%)	16.84	27.91	31.26	31.44	35.78	36.96	41.64	44.11	46.50	49.14
	S.D. (%)	0.76	0.76	0.51	1.04	0.74	0.86	1.06	1.22	1.10	1.31
	C.O.V. (%)	4.51	2.81	1.63	3.31	2.07	2.37	2.55	2.77	2.37	2.63

Table 4 PL values determined by the thread-rolling method and the Fall Cone method

		PL (%)									
	Sample	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
$PL_{thread-rolling}$	PL_{max} (%)	11.65	21.63	23.16	25.56	23.88	26.18	30.09	27.19	28.77	30.51
	PL_{min} (%)	9.24	18.21	20.68	21.71	20.14	23.41	26.19	24.10	26.14	27.16
	ΔPL (%)	2.41	3.42	2.48	3.85	3.74	2.77	3.90	3.09	2.64	3.35
	PL_{mean} (%)	11.37	19.55	21.93	23.66	22.03	24.81	27.59	25.75	27.97	28.73
	S.D. (%)	0.78	1.09	0.87	1.26	0.99	0.93	1.35	1.02	1.11	1.24
	C.O.V. (%)	6.31	5.56	3.97	5.33	4.49	3.75	4.81	3.96	3.97	5.33
PL_{cone}	PL_{max} (%)	12.90	22.29	23.84	26.14	25.11	27.42	28.34	28.89	29.62	31.66
	PL_{min} (%)	10.92	19.86	21.98	22.87	23.37	25.06	26.59	26.66	27.03	28.14
	ΔPL (%)	1.98	2.43	1.86	3.27	1.74	2.36	1.75	2.23	2.59	2.91
	PL_{mean} (%)	11.56	20.74	22.79	23.59	24.06	26.18	27.45	27.24	28.16	30.50
	S.D. (%)	0.62	0.70	0.62	1.24	0.58	0.77	1.12	0.63	0.96	1.06
	C.O.V. (%)	4.96	3.35	2.71	5.18	2.41	2.94	4.08	2.31	3.41	3.59

The correlation factor (R^2) shows how close the calculated values are to the measured values. Theoretically, the maximum value of the correlation factor is $R^2 = 1$. In this case, the calculated values would be identical to the measured values. A higher correlation factor indicates a smaller difference between calculated and measured values (better regression line). Figure 4 shows the linear correlations for the values obtained when determining the liquid limit and plastic limit. The polynomial regression line has a higher correlation factor than the linear regression line (0.9891 vs. 0.9786), as well as a significantly smaller deviations of the calculated values from the measured ones (≤ 0.88% vs. ≤ 1.43%). Thus, the polynomial regression line $y = 0.009x^2 + 0.52x + 5.0972$ was chosen as adequate for the mathematical representation of the "LL_{cone}–LL_{cup}" correlation, whereas the polynomial regression line $y = –0,0048x^2 + 1,1685x – 0,1028$ was chosen as adequate for representation of the "PL_{cone}–$PL_{rolling}$" correlation [19,20].

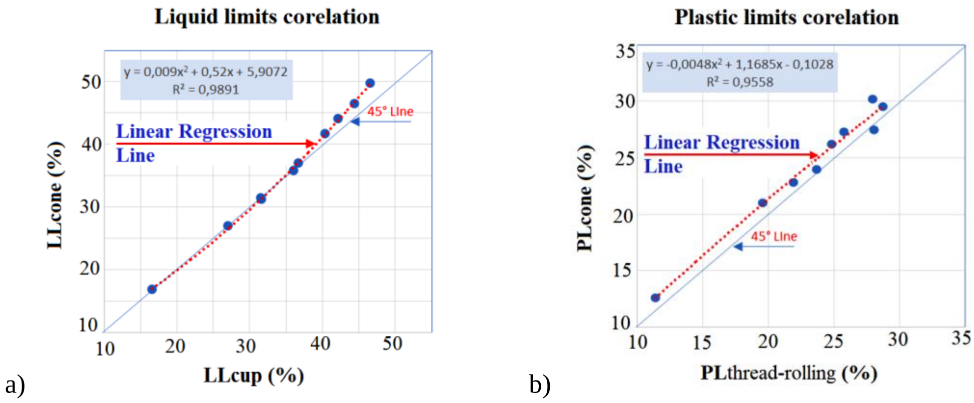

Fig. 4 Comparative analysis of the results obtained using two methods for: a) Liquid Limit; b) Plastic Limit

For the classification of soil, according to Unified Soil Classification System (USCS) (the method is prescribed by standard SRPS) it is necessary to determine LL, PL, and PI (Table 5).

Table 5 Values of LL, PL, and PI used in soil classification

Sample	Atterberg limits (%)									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
LL_{cup}	16.56	26.98	31.64	31.56	36.07	36.66	40.31	42.17	44.35	46.51
PL_{tr}	11.37	19.55	21.93	23.66	22.03	24.81	27.59	25.75	27.97	28.73
$PI_{standar}$	5.19	7.43	9.71	7.90	14.04	11.85	12.72	16.42	16.38	17.78
USCS	SC	CL	CL	ML	CI	MI	MI	CI	MI	MI
LL_{cone}	16.84	27.01	31.26	31.44	35.78	36.96	41.64	44.11	46.50	49.14
PL_{cone}	11.56	20.74	22.79	23.59	24.06	26.18	27.45	27.24	28.16	30.52
PI_{cone}	5.28	7.17	8.47	7.15	12.21	10.78	14.19	16.87	18.34	18.62
USCS	SC	CL	CL	ML	CI	MI	MI	MI	MI	MI

The plasticity index is the range of water contents where the soil exhibits plastic properties. Soils with a high PI are classified as clays and those with a lower PI are classified as silts. Table 5 shows the calculated PI values for each of the ten samples. The values of $PI_{standard}$ are calculated based on values of LL_{cup} obtained by the Casagrande cup, and PL_{tr} obtained by thread-rolling method. Values of PI_{cone} are calculated based on values of LL_{cone} and PL_{cone} obtained by the Fall Cone test. The USCS classification is done using a diagram proposed by Atterberg (Fig. 5). A-line divides the diagram into two parts. Silty and organic soils are defined by fields below A-line, while clayey soils are defined by fields above A-line. It can be observed that only sample S8 was classified as medium plasticity clay (CI) using the Casagrande and thread-rolling methods, while using a fall cone method it was classified as medium plasticity silt (MI). The difference in classification can also occur by using alternative equations, as Di Matteo et al. [21] presented in their research.

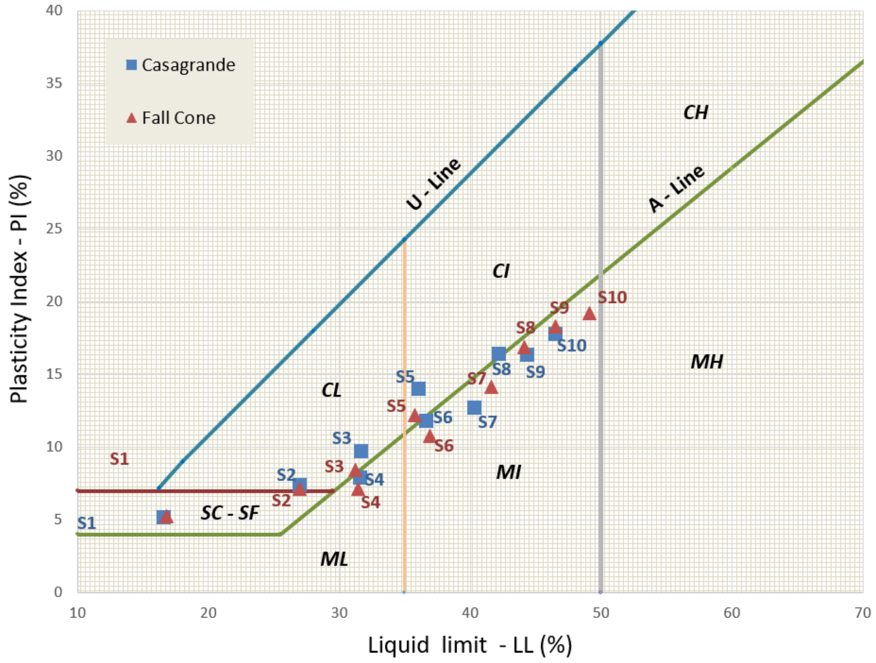

Fig. 5 Classification of tested soil samples on plasticity chart

4. CONCLUSION

The classification of fine-grained soils according to the standard SRPS EN ISO 17892-12 is based on the LL and PI values, using the plasticity chart. In order for the classification to be carried out correctly, it is necessary to first determine LL and PL as accurately as possible in laboratory tests. Based on the results of tests performed on each of the 10 fine-grained soil samples, the obtained results show that the Fall Cone method gives more reproducible results for a larger number of tests. LL values are very similar for LL < 35%, while for higher values there is a difference up to a maximum of 4.24% (Casagrande cup) and 4.01% (Fall Cone). The results presented in this paper show the successful use of the modified Fall Cone method as an alternative method for PL determination. Obtained results show that the largest difference in PL values obtained by thread-rolling method is 3.74%, whereas the use of the Fall Cone method gives PL values with the largest difference of 2.91%. Based on the comparison of statistical parameters S.D. and C.O.V. it was observed that the dispersion of the results is significantly higher for the application of the thread rolling method. On the other hand, repeatability is higher when using the Fall Cone method. The fact that the C.O.V. for the obtained results is over 90% indicates that the Fall Cone method can be used very successfully as an alternative method for determining LL and PL of fine-grained soils. In addition, the obtained S.D. and C.O.V. values indicate that the Fall Cone method is adequate for more frequent use in practice. The results presented in this paper refer to local material and it is necessary to conduct tests with samples from a wider area.

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KOMPARATIVNA ANALIZA ATERBERGOVIH GRANICA SITNOZRNOG TLA PRIMENOM RAZLIČITIH METODA

Određivanje Aterbergovih granica je veoma važno sa aspekta relevantne klasifikacije sitnozrnog tla. Ove granice se mogu odrediti prema važećem standardu SRPS EN ISO 17892-12. Standardom su propisane dve metode za određivanje granice tečenja: Kasagrandeova treskalica i metoda padajućeg konusa, i jedna metoda za određivanje granice plastičnosti: metoda ručnog valjanja valjčića vlažnog tla. U ovom radu je korišćena i metoda padajućeg konusa kao alternativna metoda za određivanje granice plastičnosti. Ispitivanja su sprovedena na deset uzoraka različitih sitnozrnih materijala, poreklom sa šireg područja grada Niša. U radu je data komparativna analiza rezultata dobijenih pri određivanju Aterbergovih granica primenom standardnih i alternativnih metoda. Takođe je izvršena i klasifikacija svih razmatranih vrsta sitnozrnog tla. Komparativna analiza pokazuje da su rezultati dobijeni primenom standardnih i alternativnih metoda bliski, ali i da je rasipanje rezultata dobijenih primenom metode padajućeg konusa značajno manje, dok je sa druge strane reproduktivnost veća.

Ključne reči: *sitnozrno tlo, granica tečenja, granica plastičnosti, indeks plastičnosti, metoda padajućeg konusa*