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Determination of the Atterberg limits using a Fall cone device on low plasticity silty sands

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Abstract

The Fall cone liquid limit testing procedure for low plasticity soil mixtures with sand, including the sample preparation procedure and the implementation of Fall cone plastic limit determination suggestions are covered within this research. A Fall cone apparatus was used in order to determine the liquid and plastic limits of soil types, for which the Casagrande cup and thread rolling methods proved inapplicable. Several issues are addressed concerning standardized sample mixture preparation and cup filling procedures for liquid limit testing, as well as the applicability of single measurements per moisture content and the effect of curing time on data gain quality. Both liquid and plastic limit testing results show a solid and expected linear trend of high precision. Liquid limit testing results correlate well with the existing data which suggests the Fall cone method as a unique liquid limit testing method for mixtures of low plasticity clays with sand. Plastic limit determination methods results show a deviation from values obtained with the classical Casagrande's thread rolling method which could be caused by the bias in the tested soil type or apparatus. Test results are presented numerically and graphically and discussed with a focus on the given method applicability for determining Atterberg limits of low plasticity soil mixtures with sand.

Keywords:

Atterberg limits; Fall cone; sand-fines mixtures; kaolinite clay

1. Introduction

Although originally developed as a strength test, the Fall cone method (hereinafter FCM) application to soil's liquid limit determination has been recognised due to the relatively easy, consistent and reproducible data gain. It has been in use for over 50 years and represents a standardized European and British method for liquid limit determination. Several suggestions backed with experimental data are given for the plastic limit determination with the Fall cone device (hereinafter FC) although these remain unstandardized.

Since this research is focused on the use of the FC to determine liquid and plastic limits of low plasticity soil mixtures with sand, a short introduction on the soils limit consistencies and the use of the FCM for their determination is given.

Atterberg limits were first introduced by Atterberg (**Atterberg, 1911**) as a method of defining the limit consistency of fine-grained soils based on water content. In other words, these limits represent the water content at which the soil changes from a solid to a semisolid state (shrinkage limit), from a semisolid to a plastic state (plastic limit), and from a plastic to a liquid state (liquid limit).

Atterberg's procedure for the plastic limit test was further modified by Terzaghi (**Terzaghi, 1926**), while for the liquid limit test, Atterberg's procedure was developed into a percussion cup test technique by Casagrande (**Casagrande, 1932**). The liquid and plastic limit testing procedures introduced by Atterberg and modified by Terzaghi and Casagrande presently remain unaltered.

Limit consistency is further expressed through the plasticity index (PI), as a measure of the soil's plasticity. The plasticity index is defined as the difference between the liquid limit (LL) and the plastic limit (PL) or as the statistical range of the soil's plastic state water content. The plasticity index is finally used to classify clayey and silty soils by use of a plasticity chart and, thanks to abundant and lengthy research so far, can also be correlated with numerous soil engineering characteristics such as compaction, compression and consolidation parameters, internal friction angle, undrained shear strength and swelling potential of a soil (**Karakan, 2022**).

Another two useful parameters obtained from the plasticity index are the activity (AI) and the liquidity index (LI). The activity of the soil is defined as the ratio of

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the plasticity index to the clay size (< 2.0 μm) fraction, **Equation 1**.

$$AI = \frac{PI}{Cl_f} \quad (1)$$

Where:

PI – plasticity index;

Cl_f – clay fraction (< 2.0 μm).

Generally, an increase in the soil's activity indicates the importance of the clay fraction influence on soil properties and soil's susceptibility to changes, since both the type and amount of clay influence the overall soil's properties (**Mitchell and Soga, 2005**). The liquidity index is defined as the ratio of the difference between natural water content of sample and plastic limit to the plasticity index of the soil.

The liquidity index relation to Atterberg limits is defined in **Equation 2**.

$$LI = \frac{w - PL}{PI} \quad (2)$$

Where:

LI – liquidity index;

w – natural water content (%);

PL – plastic limit (%);

PI – plasticity index (%).

The liquidity index correlates well with consolidation pressure, shear strength and sensitivity properties of fine-grained soils (**Skempton and Northey, 1952**).

There are two globally standardized methods used for the determination of the liquid limit and one method along with several recommendations for the determination of the plastic limit of the soil. Methods initially presented by British Standard (**BS 1377-2, 1990**) and the American Society for Testing and Materials (**ASTM D4318-10, 2010**) are the "Casagrande cup" method for the determination of the liquid limit, and Casagrande's "thread rolling" method for the determination of the plastic limit of the soil.

More recent European and British Standards exist (**BS EN ISO 17892-12:2018, 2018**) and its Fall cone method description and testing procedure are somewhat different than the procedure described in **BS 1377-2, 1990**. The recent standard excludes the option of three successive tests within the 1.0 mm penetration depth range for valid FC test data and narrows the valid data range from 15 - 25 mm penetration depth for a 30°cone apex and 80g cone FC devices. These options negatively influence the data gain in the FC testing of low plasticity soils with sand due to inconsistent data and high scatter. Also, the **BS 1377-2, 1990** was used by previous researchers for the FCM Atterberg limits determination (**Feng, 2001; Evans and Simpson, 2015**). Therefore, for the purpose of easier data gain and consistent correlation with existing test results, the data within this research was obtained according to **BS 1377-2, 1990** specifications.

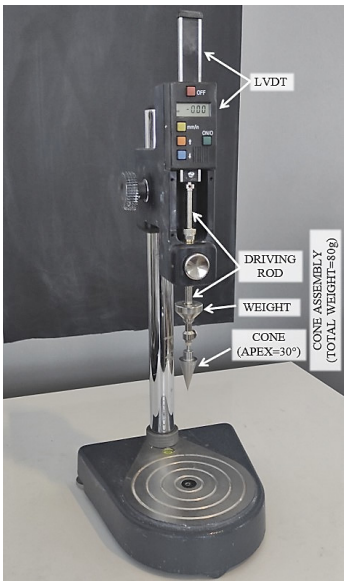

Figure 1: Fall cone device with 30°cone apex and 80g cone assembly weight according to **BS 1377-2, 1990**

The FCM provided an alternative way of determining the liquid limit of the soil and became a widely used and standardized method. The ASTM standards kept the original "Casagrande cup" as a unique liquid limit determination method without mentioning the alternative FCM for liquid limit determination, regardless of several recommendations on its applicability and advantages (**Sherwood and Ryley, 1970; Evans and Simpson, 2015**). Further research on the FCM provided recommendations on the use of the FC presented in **Figure 1**, to determine the plastic limit of the soil.

Data used for this research presents the experimental results from the determination of Atterberg limits with the FCM for several artificial soil mixtures used in small-scale slope models. To properly assess the data obtained, a short review of processed data and known and available methods with additional suggestions are given in the following section.

2. Fall cone method background

Although the initial Casagrande cup and thread rolling method for determining the liquid and plastic limit of the soil is still widely used, numerous researchers (**Sherwood and Ryley, 1970; Houlsby, 1982; Medhat and Whyte, 1986; Stone and Phan, 1995; Evans and Simpson, 2015**) imply that both methods suffer from inconsistent results that are highly reliant on the operator level and often have poor reproducibility. In comparison, the FCM for the determination of liquid limit has proven to be easier to operate with, with more consistent and reproducible results obtained than with the Casagrande cup method.

Regardless of the aforementioned suggestions, the FCM was used for this research in an attempt to deter-

mine the liquid and plastic limit of low plasticity soils with sand since the Casagrande cup and thread rolling methods have practically proven to be inapplicable for such soil types due to the difficulty of cutting a standardized groove in the cup and a tendency of low plasticity soils to slide in the cup or to liquefy with shock rather than flow (**Sherwood and Ryley, 1970**). Alternatively, for plastic limit determination of soil mixtures with sand, it was impossible to reach a 3 mm thread thickness with Casagrande's thread rolling method at any moisture content.

The FC was initially developed in Sweden in between 1914 and 1922 by the "Geotechnical Commission of the Swedish State Railways" as a method for the determination of the clay specimens' undrained shear strength (**Hansbo, 1957**). Since the introduction of the FC, numerous researchers implemented it in their research. An FC is essentially a strength test where the liquid limit represents the water content at which soil has a certain standard undrained shear strength (**Wroth and Wood, 1978**).

In the early years since the FCM was introduced, many researchers used different, unstandardized cones for the determination of both undrained shear strength and the liquid limit of the soil. The FC and FCM according to **BS 1377-2, 1990** were applied within this research. This particular method, developed in France by the Laboratoire Centraldes Pontes et Chaussees in 1966, uses a cone of a total apex angle of 30 ± 1° fixed to a vertically sliding shaft with a total assembly (cone and shaft) mass of 80.0 ± 0.1 g (**Sherwood and Ryley, 1970**). According to this method, the liquid limit is defined as the soil's water content at which the cone penetrates the soil sample 20 mm from the soil surface (cone's starting position) in 5.0 ± 0.5 s.

Both the theoretical and analytical background for the existing FCM data assessment originates from the detailed research of the clay minerals sensitivity (**Skempton and Northey, 1952**), where the given soil's shear strength and consolidation pressure correlation to the liquidity index was given. Such interpretation suggests that the shear strength of soil at the plastic limit is about a hundred times greater than the one at the liquid limit (**Skempton and Northey, 1952; Hansbo, 1957; Wroth and Wood, 1978**). This provided a direct relationship between the water content and the undrained shear strength of the soil (**Equation 3**), plotted on a semi-logarithmic scale (**Wroth and Wood, 1978**).

$$w + A \cdot \log s_u = \text{constant} \tag{3}$$

Where:

w – water content (%);

$A = PI/2$ – material constant;

s_u – undrained shear strength (kPa).

By correlating the FCM results with shear strength and compression index, it was suggested that estimations of shear strength depend only on the liquidity index and estimations of a compression index depend only on the plasticity index (**Wroth and Wood, 1978**).

Regarding the mechanical influence of the FC apparatus, detailed theoretical and experimental analysis of the soil failure zone during FC testing resulted in a simple linear relation between the penetration depth of several different cones and the undrained shear strength of the soil (**Equation 4**) (**Hansbo, 1957**).

$$s_u = \frac{K \cdot W}{d^2} \tag{4}$$

Where:

s_u – undrained shear strength (kPa);

K – constant depending on cone apex;

W – cone weight;

d – cone penetration depth (mm).

Additional theoretical and dynamic analyses of the FC tests provided a direct calculation of the tested soil's undrained shear strength at the liquid limit (**Houlsby, 1982**) and also interpreted the main factors affecting the FC penetration: the angle of the cone tip, the cone surface roughness and the rate of shear strain during penetration (**Koumoto and Houlsby, 2001**).

All the theoretical and experimental analyses of the FCM conducted so far, considering both the mechanical part of the device and comparable results of tests on different soils, established a firm theoretical background for applicable correlations of the obtained experimental data with different soil parameters.

2.1. Fall cone method for liquid limit determination

According to the **BS 1377-2, 1990**, the FCM (cone penetrometer method) is defined as the primary liquid limit testing method and the Casagrande's cup method as an alternative testing method. British Standard specifies FC apparatus characteristics, different testing methods, sample preparation procedure as well as calculation and expression of results in a test report. Two FCM for liquid limit testing are defined: (i) a definitive method and (ii) a one-point method. A definitive method for soil's liquid limit testing was used within this research and compared to the first penetration readings results.

2.2. Fall cone method for plastic limit determination

Since the FCM was globally adopted for soil's liquid limit testing, several authors gave suggestions considering the determination of the plastic limit of soil with the same apparatus.

The first given suggestion (**Wood and Wroth, 1978; Wroth and Wood, 1978**) used within this research, (hereinafter the semi-direct method) uses the difference in water content at which the cones penetrate the soil sample 20 mm, between test data series from cones of

different weight. The difference is calculated according to **Equation 5** and used for the indirect determination of soil's plasticity index according to **Equation 6**. The relation described is graphically presented in **Figure 2**. The rest of the testing procedure, sample preparation method and data evaluation remain equal to the standardized liquid limit testing method.

$$\Delta = A \cdot \log \frac{W_1}{W_2} \tag{5}$$

$$\mathrm{PI} = \frac{2\Delta}{\log \frac{W_1}{W_2}} \tag{6}$$

Where:

Δ – water content difference;
A = *PI*/2 – material constant;
$W_{1,2}$ cones of different weight ($W_1 > W_2$);
PI – plasticity index.

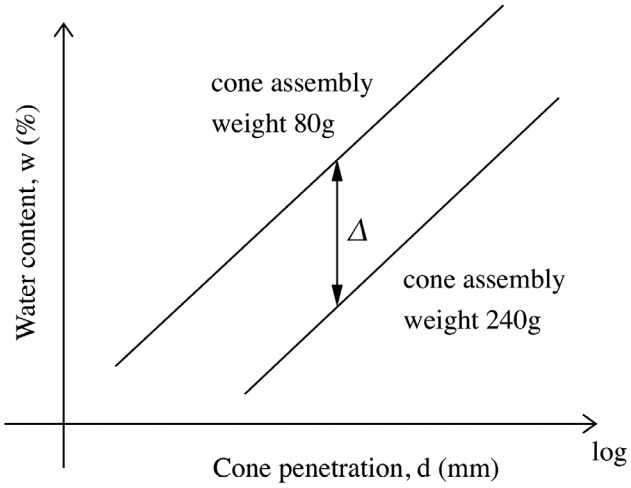

Figure 2: Measured water content difference (modified according to (**Wood and Wroth, 1978**))

An alternative method was given with an extrapolation of the FC test data trend line on a semi-logarithmic plot of the FC penetration depth value (logarithmic) against the soil's moisture content and liquidity index (**Harison, 1988**). Consistent FC testing results plotted this way have shown a characteristic trend of forming two apparently straight trend lines intersecting at 14 mm penetration depth which corresponds to a 0.77 liquidity index value or twice the soil's shear strength value than at the liquid limit. A further extrapolation of trend lines intersects the soil's liquid limit and plastic limit at a penetration depth of 20 mm and 2 mm, respectively. A similar solution (hereinafter the indirect method) for plastic limit determination was given with power law functions (**Equation 7**) to describe the variation of water content with cone penetration depth on a double-logarithmic d-w scale which forms a linear trend that intersects the soil's plastic limit water content at 2 mm penetration depth (**Feng, 2000; Feng, 2001**).

$$\mathrm{w} = \mathrm{C}_0 \cdot d^{\beta} \tag{7}$$

Where:

w – water content;
C_0 – water content intercept at d=1 mm;
d – cone penetration depth;
β – slope of the best-fit straight line.

According to the **Equation 7** the FC liquid (LL_{FC}) and plastic (PL_{FC}) limit are defined in **Equation 8** and **Equation 9**, respectively (**Shimobe and Spagnoli, 2020**).

$$\mathrm{LL_{FC}} = C_0 \cdot (20)^{\beta} \tag{8}$$

$$\mathrm{PL_{FC}} = C_0 \cdot (2)^{\beta} \tag{9}$$

FC liquid limit test results within this research were plotted on a double-logarithmic d-w plane (**Feng, 2001**), along with data for the previously mentioned plasticity index and plastic limit determination methods.

Several more direct solutions to plastic limit determination with FC devices will be mentioned. With the load control method (**Medhat and Whyte, 1986**), the weight case over the cone is adjusted to provide a load relevant to the tabular penetration depth, where the water content corresponding to 10 mm and 15 mm penetrations represent the soil's plastic limit. Another method (**Stone and Phan, 1995**) uses the extrapolation of quasi-static penetration test data for obtaining the moisture content (plastic limit) corresponding to one hundredfold increase in strength over the strength at the liquid limit. This method's progress was further upgraded with the development of an automated quasi-static FC (**Sivakumar *et al.*, 2009**). These methods were not applied in this research since the soil mixtures tested were very difficult to homogenize at the predicted testing water content (close to the plastic limit) which proved rather impractical while performing a large number of tests. A bias in results obtained during testing could also occur with inconsistent water content due to relatively rapid moisture loss in soil mixtures of low plasticity with sand.

3. Materials and methodology

3.1. Soil mixtures and sample preparation

Mixture types tested with the FCM were prepared by mixing kaolinite and quartz sand specimens with a predetermined mass ratio needed to ensure the targeted material type percentage (see **Table 1**). Drava sand represents the quartz sand fraction, obtained from an excavation pit near Osijek city, while the kaolinite was obtained from Petrokemija d.d., Kutina, as an industrial by-product. Basic physical characterisation of the used sand and kaolinite powder and mixtures were performed and doc-

Table 1: Soil mixture types with quartz sand (S) and kaolinite clay (K) mass ratios

Mixture type	S [%]	K [%]
K100	0	100
SK30	70	30
SK15	85	15
SK10	90	10

umented by (**Pajalić *et al.*, 2021; Prodan *et al.*, 2022; Pajalić, 2023**).

Initially, dry specimens were manually and carefully mixed to reduce the predicted effect of physical grinding between particles.

Prepared artificial soil mixtures were further tested according to **BS 1377-2, 1990**. The prepared sample mixture was initially sieved by wet sieving through a 425 μm test sieve. The coarser fraction was dried and weighed, while the slurry which passed the 425 μm test sieve was left in a container until the sample particles were fully sedimented and excess surface water carefully removed. Although the British Standard states that the samples should be air-dried until achieving paste-like consistency, this approach proved to be highly impractical. The mixtures with sand dried heterogeneously, creating dry aggregates at the container edges and should have been mixed through the whole drying process to ensure a homogenous paste-like sample. Alternatively, the highly saturated pure kaolinite samples took several days to air dry to the moisture content near the liquid limit. Taking into account that no significant changes like loss of kaolinite's structural water or density including changes in structure and fabrics occur below 200°C (**Sen, 1962**), as well as the inertness of the quartz sand particles used in soil mixtures, sedimented samples were oven-dried at 105°C. After the drying process, de-aired water in a mass ratio for optimal water content was added and the mixture was once again carefully mixed and homogenized to optimal water content. Each soil sample prepared this way was sealed in a container to prevent moisture loss and left overnight for approximately 24 hours before testing in order to balance potential changes caused by kaolinite clay surface electrical forces, and cation exchange capacity (**Mitchell and Soga, 2005**).

3.2. Liquid limit testing procedure

For the FC liquid limit testing of individual soil samples, the definitive method (**BS 1377-2, 1990**) was used. The definitive method requires two successive penetration depth readings within the 0.5 mm range or three successive readings within the 1.0 mm range.

The sample was thoroughly mixed before testing and pushed down into a 40 by 55 mm cylindrical specimen cup, with caution not to trap air. Personal experience with pure clay (kaolinite) samples, suggested that circular smearing of the sample along the edges of the cup in both ways while using solid pressure tends to nullify most of the trapped air. Clay samples tend to open additional pores if smeared in the cup with weak or moderate relative pressure. Sharply tapping the specimen cup on a flat surface pushes pores to the surface and evens the soil laterally in the cup, but it also tends to push free water to the soil's surface. The effect this occurrence could have on test results was ignored within this research, although care was taken not to exceed this effect during preparation. Tapping causes shock-enforced soil compression and pore water loss observed on the specimen surface which suggests a hardening of the soil, although rapid upward seepage could cause a surface disturbance and local weakening of the tested specimen. Furthermore, such shock-enforced loading caused a liquefaction like phenomena that can separate finer kaolinite particles form the sand particles. For soil samples with sand and low clay content, tapping the cup proved inapplicable since it tended to launch the entire sample out of the cup. This effect seems to gradually diminish with increasing clay and/or water content, although it proved adequate to only push and smear low clay content samples into the cup without tapping it.

When the specimen cup was appropriately filled, excess soil was removed with the straight edge of a palette knife to form a smooth level surface. For soil samples with sand and low clay content, removing excess soil causes surface disturbance due to the movement of the irregularly shaped sand grains. A relatively smooth surface in such soils was achieved by gently cutting off the excess soil. With increasing clay content, cutting off excess soil loses applicability since the clay particles tend to stick to the knife's surface thus disturbing the sample surface. During the sample preparation procedure, different cup-filling procedures within this research were optimized for both pure clay (kaolinite) samples and low plasticity soil mixtures with sand.

For pure kaolinite samples, existing suggestions on cup filling procedures (**BS 1377-2, 1990**) can be applied - filling and tapping the cup and removing the excess soil to form a smooth and flat surface. Circular smearing of the sample along the edges of the cup in both ways while using solid pressure tended to nullify most of the pores in the pure clay sample thus improving the testing procedure.

For soil samples with sand and low clay content, pushing and smearing samples into the cup proved adequate with a remark that tapping the cup proved inapplicable since it tended to launch the entire sample out of the cup. Standardized removal of excess soil causes surface disturbance due to the movement of the irregularly shaped sand grains. A relatively smooth surface in soil mixtures with sand was achieved by gently cutting off the excess soil, instead of removing it.

Observations on differences in sample preparation and cup-filling procedures for different soil samples sug-

Table 2: Summary of results obtained with the implemented testing methods

Mixture type	LL_{FC}	LL_C	PL_{ww}	PL_f	PL_C	PI_{ww}	PI_f	PI_C
K100	48.3	53.0	19.3	21.6	30.0	28.9	26.7	23.0
SK30	24.0	N/A	14.4	13.8	N/A	9.6	10.2	N/A
SK15	17.9	N/A	11.3	9.6	N/A	6.7	8.3	N/A
SK10	17.9	N/A	5.7	5.8	N/A	12.2	12.1	N/A

LL_{FC} = liquid limit - definitive Cone penetrometer method (**BS 1377-2, 1990**);
LL_C = liquid limit - Casagrande cup method (**BS 1377-2, 1990**);
PL_{ww} = plastic limit (**Wood and Wroth, 1978**);
PL_f = plastic limit (**Feng, 2001**);
PL_C = plastic limit - Casagrande thread rolling method (**BS 1377-2, 1990**);
PI_{ww} = plasticity index (**Wood and Wroth, 1978**);
PI_f = plasticity index (**Feng, 2001**);
PI_C = plasticity index - Casagrande cup and thread rolling method (**BS 1377-2, 1990**).

Table 3: Kaolinite clay mineral Atterberg limits values determined with FCM

Liquid limit	Plastic limit	Source
55	27	(**Stone and Phan, 1995**) [1]
50	23-26	(**Feng, 2000**) [2]
50-72	25-33	(**Feng, 2001**) [2]
70	28	(**Feng, 2004**) [2]
68	34	(**Sivakumar *et al.*, 2009**) [1]
48-49	24-25	(**Evans and Simpson, 2015**) [2]
62	37	(**Karakan, 2022**) [2]
48.3	21.6	This research

[1] – plastic limit determined with quasi-static penetration data
[2] – plastic limit determined on a double logarithmic d-w scale

gest a need for more specified standardized instructions concerning these issues.

With the prepared specimen in the cup, the rest of the testing procedure was performed according to the **BS 1377-2, 1990**. The effect of different curing times on test results was observed in some samples by leaving the sample sealed for different periods of time (1 min, 30 min, 60 min) after each addition of water between penetration tests.

The results of performed tests as datapoints are plotted in a double logarithmic scale with penetration depth on "x" axis and water content on "y" axis. A trendline is plotted over the datapoints by applying **Equation 7**. For each soil mixture a regression analysis was performed and the correlation coefficient (R^2) was calculated for the best fit parameters determined (**Draper and Smith, 1998; Chapra and Canale, 2015**).

3.3. Plastic limit determination

As was mentioned in the Introduction, a couple of existing suggestions on determining the soils plastic limit with FC device were implemented within this research:

- the semi-direct method which uses calculation of the soils plasticity index from differently weighed cones penetration data (**Wood and Wroth, 1978**),
- the indirect method which uses the double-logarithmic extrapolation of the penetration depth value (logarithmic) against the soil's water content (**Feng, 2001**).

The semi-direct method uses the difference in water content obtained from a pair of standard FC tests with different cone assembly weight. The indirect method uses the extrapolation of a plotted trend line to a 2 mm penetration depth value on a double-logarithmic d-w scale, which intersects with the plastic limit of the tested soil.

Both methods for plastic limit determination implemented within research are based on a statement of an increase in soil's shear strength at the plastic limit over the strength at the liquid limit (**Wroth and Wood, 1978; Feng, 2000**).

4. Results and discussion

Results obtained with the FC device were analysed according to the **BS 1377-2, 1990** and existing suggestions (**Wood and Wroth, 1978; Feng, 2001**), in order to determine the tested soil's liquid and plastic limits. All testing results are summarized in **Table 2**. The results are presented in **Figure 3** and correlated in order to determine the trend of the soil's response to a certain testing method. For the purpose of correlation, several tests on pure kaolinite samples with the Casagrande cup and thread rolling methods were conducted. Blue marks represent the data obtained for a cone tip with a cone apex angle of 30° and total mass of 80 g while the orange marks represent the data obtained for the total mass of 240 g. The blue trendline represents the power function with the appropriate best-fit parameters obtained by regression analysis for a total mass of 80 g, while the orange trendline is plotted for a total mass of 240 g. The blue star marker represents the value of liquid limit at the penetration depth of 20 mm for a total mass of 80 g

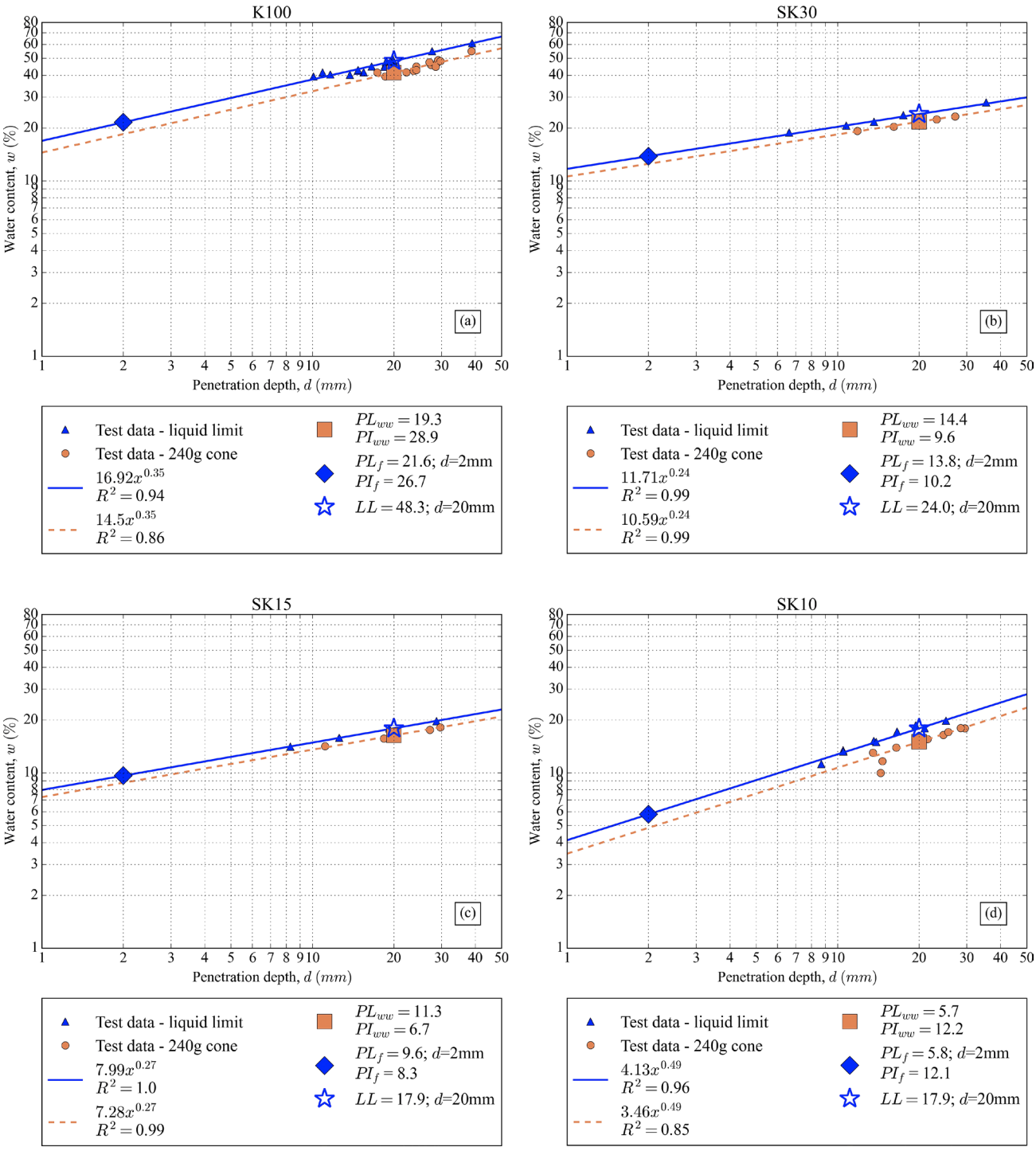

Figure 3: Double logarithmic d-w plot of the FC test results on the mixture types according to **Table 1**: (a) K100, (b) SK30, (c) SK15, (d) SK10

while the orange square represents the water content value at the penetrating depth of 20 mm for a total mass of 240 g, which is used to calculate the soils plasticity index according to **Wood and Wroth, 1978**. Although the semi-direct method specifies the semi-logarithmic scale for data presentation (**Wood and Wroth, 1978**), results were plotted on a double-logarithmic scale in order to extrapolate the plastic limit at the penetrating depth of 2 mm for a total mass of 80 g (**Feng, 2001**).

Test results on pure kaolinite clay samples were also correlated with the existing data on kaolinite Atterberg limits' range determined with FCM which are summarized with **Table 3** and plotted on **Figure 4.**

4.1. Liquid limit determination - Cone penetrometer definitive method

The results in **Table 2** based on the procedure according to **BS 1377-2, 1990**, FCM are plotted on a double-

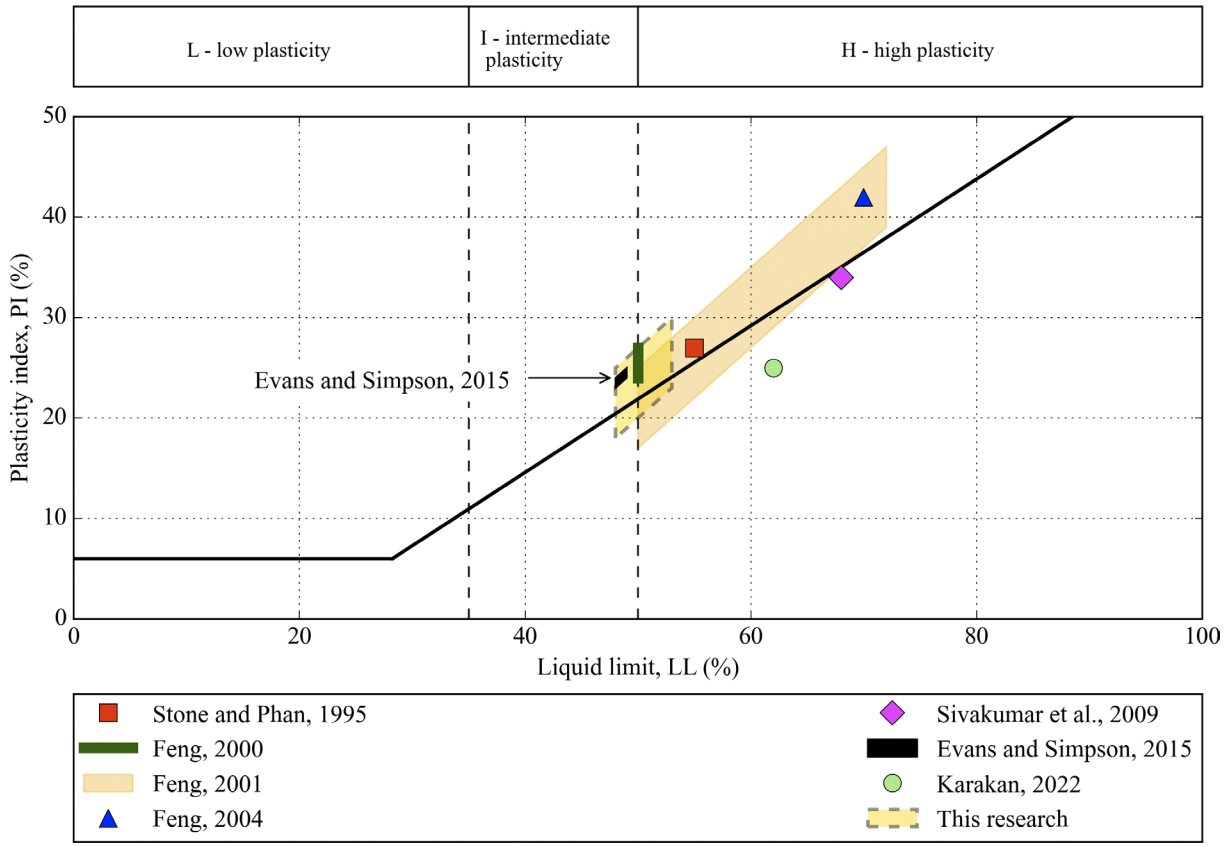

Figure 4: Plasticity of kaolinite clay mineral according to **Table 3**

logarithmic d-w scale (see **Figure 3**). The plotted liquid limit testing results show a solid and expected linear trend of high precision with R^2 values varying from 0.94 to 1.00. The SK10 samples were tested at a very low moisture content (below the measured plastic limit) and the obtained results showed a drop in penetration depth with increasing moisture content up to approximately 10% water content, which correlates well with the existing data on the FCM at soil mixtures' semi-solid state (**Karakan, 2022**). In order to obtain an extrapolative trend for the given specimen (SK10), penetration depths below 8% moisture content were neglected for regression analysis. Testing close to the plastic limit also resulted in a high data scatter which contributed to a lower R^2 value. Data obtained for K100 sample correlates well with the existing data presented in **Table 3**. A comparison of consistent data from different sources suggests that in the range of soils liquid limits <120%, the correspondence between the Casagrande's cup method and FCM is good with a relative error of ± 10% (**Shimobe and Spagnoli, 2019**) which is confirmed with the present research (see **Table 2**) where the FC liquid limit value of the K100 sample is approximately 10% lower than that obtained with the Casagrande's cup method. High data precision and continuous trend in liquid limit increase with increasing clay (kaolinite) content fairly suggest FCM applicability as a unique liquid limit testing method for mixtures of low plasticity clays with sand.

4.2. Plastic limit determination - the semi-direct method

Similar to liquid limit testing data, the plotted data from 240 g cone tests (see **Figure 3**) show a solid and expected linear trend of high precision with R^2 values varying from 0.85 to 0.99. Data obtained with a semi-direct method, if compared to existing data (see **Table 3**), resulted in a relatively high plasticity index and low corresponding plastic limit of the pure kaolinite (K100) sample. Values of the plastic limit and plasticity index determined for the K100 sample differ from results obtained by Casagrande's thread rolling method by approximately 36% and 20% respectively (see **Table 2**). It was unsure if this apparent inaccuracy in results was caused by the aforementioned bias in material or apparatus, although the reason could also lie in the applicability of the semi-direct method for low plasticity soil mixtures. Data obtained for SK30 and SK15 mixtures show a logical and relatively consistent drop in Atterberg limits' values with decreasing clay content. The difference in SK10 sample's plasticity index value is probably caused by high data scatter and low precision of performed tests data near the specimen's plastic limit water content.

4.3. Plastic limit determination - the indirect method

The results (see **Table 2**) based on the procedure defined by the **BS 1377-2, 1990** FCM, are plotted on a

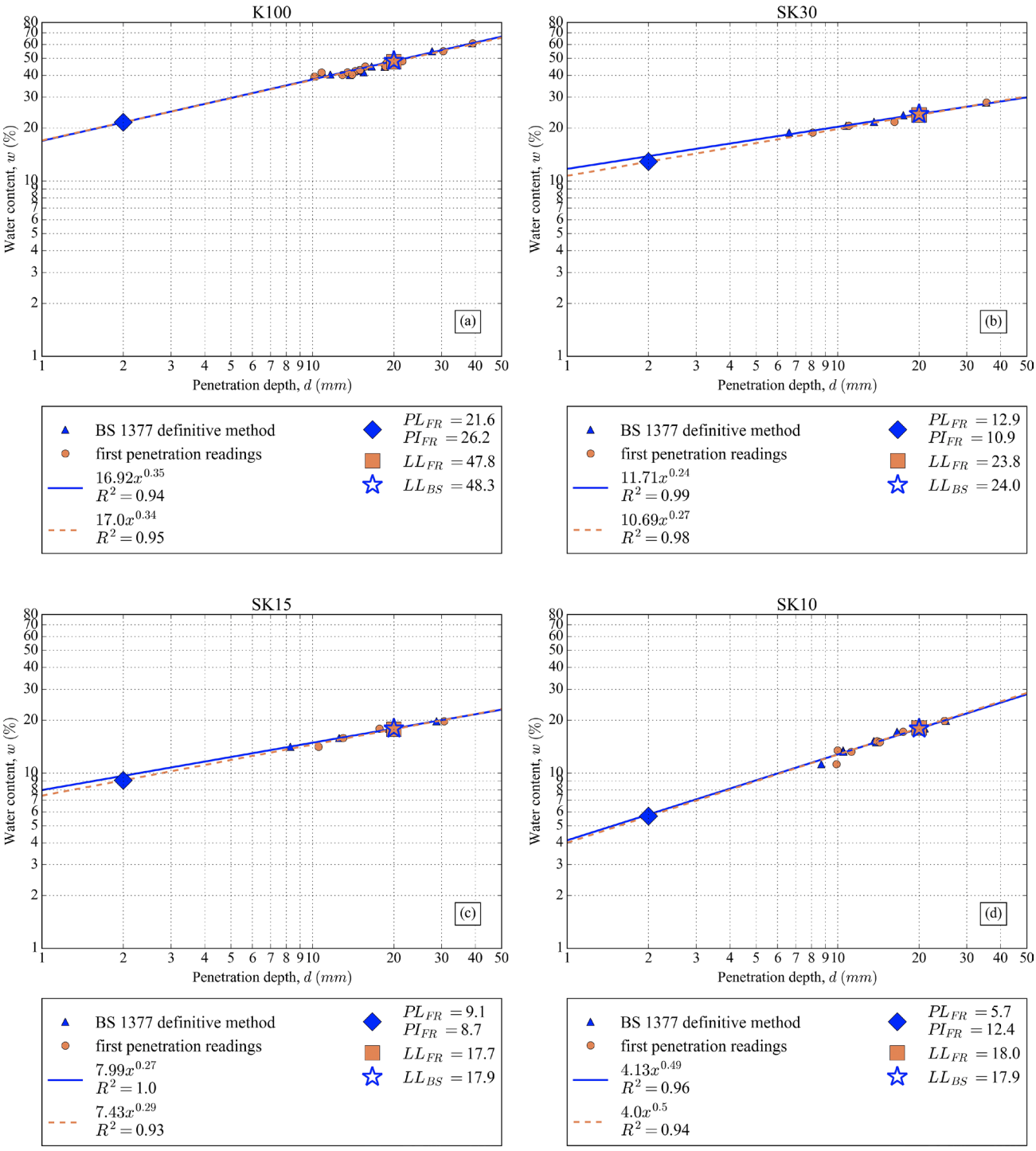

Figure 5: Fall cone first penetration readings results comparison for the mixture types according to **Table 1**: (a) K100, (b) SK30, (c) SK15, (d) SK10

double-logarithmic d/w scale (see **Figure 3**) in order to extrapolate obtained trend line to a 2 mm penetration depth value. For a given soil, the trend line theoretically intersects the soil's plastic limit's water content at the 2 mm penetration depth value (**Feng, 2001**).

Since this method uses the FCM testing procedure results, trend line extrapolation precision relies exclusively on the range of water content at which the soil's liquid limit was tested. For a semi-logarithmic plot (**Harison, 1988**), penetration depth readings below 14 mm are significant for plastic limit determination since the lower part (under 14 mm penetration depth) of the non-linear trend line is further extrapolated to 2 mm penetration depth. A double logarithmic plotting scale can be used (**Feng, 2001**) to bypass this issue by forming a single linear trend that can be extrapolated to 2 mm penetration depth.

Similar to the semi-direct method, data obtained with the indirect method, if compared to existing data (see

Table 4: Summary of definitive method and first penetration readings test data

Mixture type	LL_{BSd}	LL_{BS1}	PL_{BSd}	PL_{BS1}	PI_{BSd}	PI_{BS1}
K100	48.3	47.8	21.6	21.6	26.7	26.2
SK30	24.0	23.8	13.8	12.9	10.2	10.9
SK15	17.9	17.7	9.6	9.1	8.3	8.7
SK10	17.9	18.0	5.8	5.7	12.1	12.4

LL_{BSd} = liquid limit - definitive method (**BS 1377-2, 1990**);
LL_{BS1} = liquid limit - first penetration reading;
PL_{BSd} = plastic limit - definitive method (**Feng, 2001**);
PL_{BS1} = plastic limit - first penetration reading (**Feng, 2001**);
PI_{BSd} = plasticity index - definitive method;
PI_{BS1} = plasticity index - first penetration reading.

Table 3), resulted in a relatively high plasticity index and low corresponding plastic limit of the pure kaolinite (K100) sample. Obtained values for plastic limit and plasticity index differ from results obtained by Casagrande's thread rolling method (see **Table 2**) by approximately 28% and 14% respectively which is significantly less than with values obtained with the semi-direct (**Wood and Wroth, 1978**) method. Data obtained for SK30, SK15 and SK10 mixtures show a logical and relatively consistent drop in Atterberg limits' values with decreasing clay content.

The indirect method used within this research proved to be the most practical method for soil's plastic limit determination since it extrapolates existing liquid limit testing data on a linear trend line. A deviation in plastic limit values obtained for K100 sample from expected ranges for similar soils and from the classical Casagrande's thread rolling method results could be caused by the bias in material or apparatus.

4.4. Analysis of the Fall cone first penetration readings

Due to the need for two and three successive penetration readings within 0.5 mm and 1.0 mm respectively (**BS 1377-2, 1990**), as well as the probable inexperienced operator imprecision, a relatively wide range of penetration depths were measured with high inconsistency and the number of tests needed to achieve the satisfactory sequent results. Therefore, data readings (see **Table 4**) for Atterberg limits determination within standard's limitations (2-3 successive test within a certain range) are plotted alongside the first penetration readings results (see **Figure 5**) regardless of the range and number of tests in order to try and evaluate the deviation in results and applicability of the single measurements per moisture content for liquid and plastic limit determination of low plasticity soil mixtures with sand. Soils plastic limit and corresponding plasticity index were determined by extrapolation of the obtained trend line to a 2 mm penetration depth value (**Feng, 2001**).

The blue marks represent the data obtained according to the definitive method while the orange marks represent the first penetration readings. The blue trendline represents the power function with appropriate best-fit parameters obtained by regression analysis for the definitive method's measurements, while the orange trendline is plotted for the first penetration readings data. The blue star marker represents the value of liquid limit obtained with the definitive method while the orange square represents the liquid limit obtained with the first penetration readings data. The blue diamond presents a plastic limit at the penetrating depth of 2 mm for the orange (first penetration readings) trendline (**Feng, 2001**).

Data obtained with first penetration readings correlates well with the data obtained with the definitive method (< 1% difference for the liquid limit values) and values obtained for plastic limit and plasticity index differ by approximately 0-7% and 2-6% respectively. Data obtained suggests that the first penetration readings can be effectively applied as a valid liquid and plastic limit testing method for mixtures of low plasticity clays with sand.

4.5. Effect of sample curing time

On the K100 sample, a different curing time was introduced by leaving the sample sealed for different period of times (1 min, 30 min, 60 min) after each addition of water between penetration tests. Changes in penetration depth range values and number of penetration tests needed to obtain valid data for definitive method were plotted against curing time (see **Figure 6**) in order to see its effect on testing results progression.

Data obtained show a general decrease in the penetration depth range values and number of penetration tests with an increase in curing time. The number of penetration tests median value drops from 3 to the number of 2 tests after 60 minutes of curing time, while the number of tests needed for obtaining valid data drops significantly after 30 minutes and even more after 60 minutes of curing time. Similar data follows the penetration depth range values with a general decrease in their median value and depth range with an increase in curing time. Both the median value and the majority of the penetration depth range values drop below the targeted values

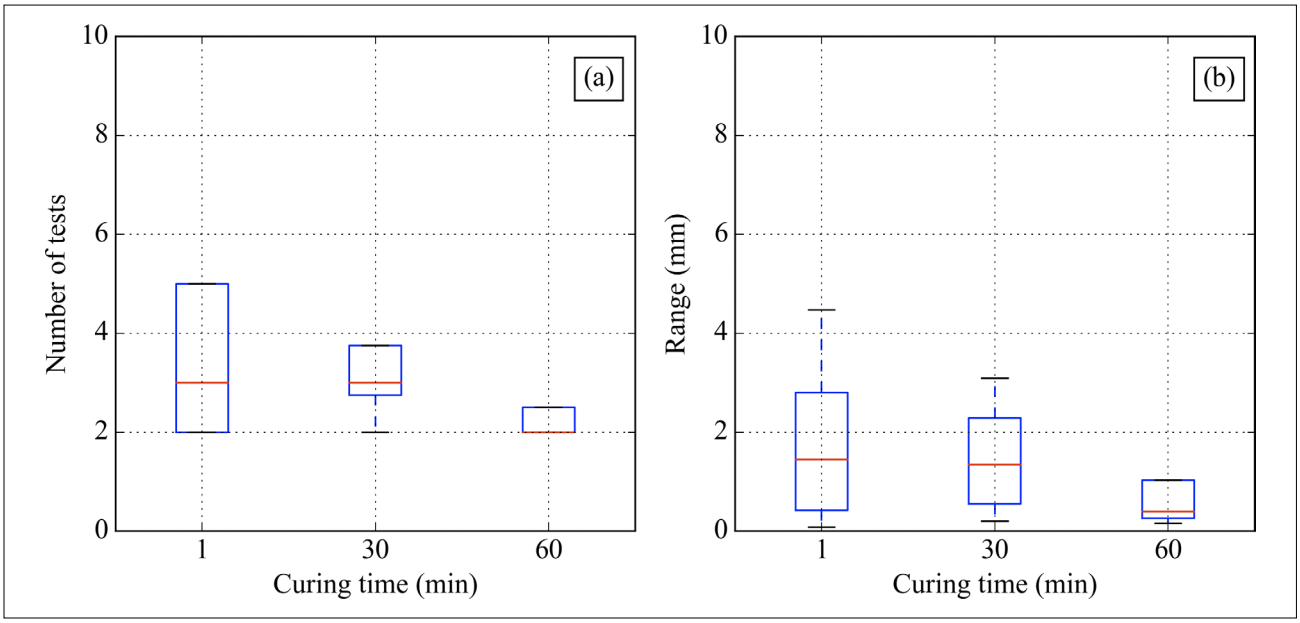

Figure 6: Effect of curing time: (a) number of penetration tests needed and (b) penetration depth range values

of 0.5 mm and 1.0 mm respectively after 60 minutes of curing time. Implemented curing time after each addition of water between penetration tests resulted in significantly better data quality. For the pure kaolinite sample (K100) tested, it appears that a curing time of 60 minutes can be applied to obtain more valid successive test results.

5. Conclusion

The present research summarizes the results of the Atterberg limits determination using FC. The primary goal was to evaluate the FCM liquid limit testing procedure according to **BS 1377-2, 1990**, including suggestions for the plastic limit determination (**Wood and Wroth, 1978; Feng, 2001**) applicability for the determination of Atterberg limits of low plasticity clays with sand.

Based on this paper's research data, several conclusive remarks can be drawn concerning the FC liquid limit testing procedure for low plasticity soil mixtures with sand, including the sample preparation procedure and the implementation of FC plastic limit determination suggestions:

- The sample preparation procedure indicated an impracticability of the air-drying procedure for sieved and sedimented sample mixtures (**BS 1377-2, 1990**) due to the heterogeneous drying of the samples with sand and very slow, air-drying procedure of the pure kaolinite samples. Since kaolinite's structural water or density including changes in structure and fabrics occur above 200°C (**Sen, 1962**), this issue was bypassed by oven-drying the sample mixtures at 105°C, although an alternative solution should be given regarding different types of clay minerals in soil mixtures.
- Different cup-filling procedures within this research were optimized for both pure clay (kaolinite) samples and low plasticity soil mixtures with sand. For pure kaolinite samples, existing suggestions on cup filling procedures (**BS 1377-2, 1990**) can be applied - filling and tapping the cup and removing the excess soil to form a smooth and flat surface. Circular smearing of the sample along the edges of the cup in both ways while using solid pressure tended to nullify most of the pores in the pure clay sample thus improving the testing procedure. Sharply tapping the specimen cup tends to push free water to the soil's surface, although the effect of this occurrence was unknown and ignored within this research. For soil samples with sand and low clay content, pushing and smearing samples into the cup proved adequate with a remark that tapping the cup proved inapplicable since it tended to launch the entire sample out of the cup. The standardized removal of excess soil causes surface disturbance due to the movement of the irregularly shaped sand grains. A relatively smooth surface in soil mixtures with sand was achieved by gently cutting off the excess soil, instead of removing it. With increasing clay content, cutting off excess soil loses applicability since the clay particles tend to stick to the knife's surface thus disturbing the surface. Observations on differences in sample preparation and cup-filling procedures for different soil samples suggest a need for more specified standardized instructions concerning these issues. The plotted liquid limit testing results show a solid and expected linear trend of high precision. Data obtained for K100 sample correlates well with the existing data. A comparison of consistent data from different sources suggests that

in the range of soils liquid limits <120%, the correspondence between the Casagrande's cup method and FCM is good with a relative error of ± 10% (**Shimobe and Spagnoli, 2019**) which is confirmed with the present research where the FC liquid limit value of the K100 sample is approximately 10% lower than that obtained with the Casagrande's cup method. High data precision and continuous trend in liquid limit increase with increasing clay (kaolinite) content fairly suggest FCM applicability as a unique liquid limit testing method for mixtures of low plasticity clays with sand.

- Concerning the semi-direct method (**Wood and Wroth, 1978**) for soil's plastic limit determination, the plotted data from 240 g cone tests show a solid and expected linear trend of high precision. If compared to the Casagrande's thread rolling data, a relatively high plasticity index and low corresponding plastic limit of the pure kaolinite (K100) sample were determined, differing by approximately 20% and 36% respectively. This apparent inaccuracy in results could be caused by the bias in material or apparatus, although the reason could also lie in the applicability of the semi-direct method for low plasticity soil mixtures. A larger set of data on different soil specimens should be obtained with this method to appropriately assess these issues.
- Data obtained with the indirect method (**Feng, 2001**), if compared to the Casagrande's thread rolling data, resulted in a relatively high plasticity index and low corresponding plastic limit of the pure kaolinite (K100) sample, differing by approximately 14% and 28% respectively. The indirect method used within this research proved to be the most practical method for soil's plastic limit determination since it extrapolates existing liquid limit testing data. A deviation in plastic limit values obtained for K100 sample from the classical Casagrande's thread rolling method results could be caused by the bias in material or apparatus. As with semi-direct method, a larger set of data on different soil specimens should be obtained with this method.
- Data obtained with first penetration readings correlates well with the data obtained with the definitive method (< 1% difference for the liquid limit values) and values obtained for plastic limit and plasticity index differ by approximately 0-7% and 2-6% respectively. The obtained data suggests that the first penetration readings can be effectively applied as a valid liquid and plastic limit testing method for mixtures of low plasticity clays with sand.
- Implemented curing time after each addition of water between penetration tests resulted in significantly better data quality of the pure kaolinite sample (K100) and a curing time of 60 minutes can be applied in order to obtain a more valid successive test results.

Based on the obtained results and the presented observations, this paper's research contributes to the improvement and expansion of knowledge of the FCM applicability for soil's liquid and plastic limit determination. The presented results and observations are focused on artificial soil mixtures – silty sands, with quartz sand and kaolinite clay.

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SAŽETAK

Određivanje Atterbergovih granica pomoću padajućega šiljka na prahovitim pijescima niske plastičnosti

Ovim istraživanjem obuhvaćen je postupak ispitivanja granice tečenja metodom padajućega šiljka za niskoplastične mješavine tla s pijeskom uključujući postupak pripreme uzorka i provedbu postojećih prijedloga za određivanje granice plastičnosti. Metoda padajućega šiljka korištena je za određivanje granica tečenja i plastičnosti za tipove tla, gdje metode Casagrandeove zdjelice i valjanja valjčića nisu bile primjenjive. Obuhvaćeno je i nekoliko problema vezanih za standardiziranu pripremu mješavine uzoraka, postupak punjenja čašice s uzorkom za potrebe testiranja granice tečenja, primjenjivost pojedinačnih mjerenja po sadržaju vlage te utjecaj vremena zrenja glinovitoga uzorka na kvalitetu dobivenih podataka. Rezultati ispitivanja granica tečenja i plastičnosti pokazuju solidan i očekivan linearni trend visoke preciznosti. Rezultati ispitivanja granice tečenja dobro koreliraju s postojećim podatcima, što upućuje na dobru primjenjivost metode padajućega šiljka za potrebe ispitivanja granice tečenja za mješavine tla s pijeskom niske plastičnosti. Primijenjene metode određivanja granice plastičnosti pokazuju odstupanje od vrijednosti dobivenih klasičnom Casagrandeovom metodom valjanja valjčića, što bi moglo biti uzrokovano utjecajem ispitivane vrste tla ili uređaja. Rezultati ispitivanja prikazani su numerički i grafički s naglaskom na primjenjivost upotrijebljenih metoda za određivanje Atterbergovih granica niskoplastičnih mješavina tla s pijeskom.

Ključne riječi:
Atterbergove granice, padajući šiljak, mješavine pijeska i gline, kaolinitna glina

Author's contribution

Davor Marušić (1) (PhD student, research assistant) conducted part of the literature research and the aimed laboratory testing of the given soil types, including observations of the implemented testing methods and contributed to the discussion considering the research results. **Vedran Jagodnik (2)** (assistant professor) conducted part of the literature research, the statistical analysis of the obtained data and contributed to the discussion considering the research results.