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Comparison of the Casagrande and Fall Cone Methods for Liquid Limit Determinations in Different Clay Soils

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ABSTRACT: The liquid limit (LL) is an important parameter for soil classification systems. The use of the cone penetrometer technique for measuring the liquid limit is an attractive alternative method since the percussion method is highly operator dependent. In this article, the importance of specifying the procedure and equipment used to determine the LL of a clay soil is highlighted using LL test results conducted on different clay soils. The results of LL, obtained by the percussion method proposed by Casagrande (LL_c) and by the penetration cone method (LL_p) on clay soils of different geological origins and plasticity were compared. The LL_p values were determined using the British cone (20 mm fall cone penetration) method. The LL_c values were determined using different hardnesses of Casagrande apparatus. The LL test results show that variations on the investigated methods depend on the mineralogy of the clay soil and the hardness base of the Casagrande cup. The data obtained for kaolinites and illites minerals or low LL soils yielded $LL_p>LL_c$. The results obtained for smectite minerals or soils with high LL values indicated $LL_p<LL_c$ and a greater dispersion among the results. Statistical analyses of residues show that empirical LL_p-LL_c correlations through a linear regression analysis should be used with caution.

Keywords: plasticity of clays, base hardness, cone penetration method, percussion cup, correlations.

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INTRODUCTION

The property that causes the clay-water system to deform continuously under a finite force, and maintain its shape when the force is removed or reduced, known as plasticity, is used in many areas of engineering and science. Several factors can affect the plasticity of clays, such as mineralogical composition, particle size distribution, organic substances, and additives (Andrade et al., 2011).

The maximum value of the water content of a clay soil in the range of plastic consistency is defined as the Liquid Limit (LL). The LL value, which may vary over a wide range, is used in the classification and preliminary evaluation of clayey soils in engineering works. Erroneous determination of LL may result in rejection of satisfactory materials, even acceptance of inappropriate materials, or lead to expensive treatments.

Traditionally, the most used procedure to determine the LL is the percussion method standardized by Casagrande (1932). However, the Casagrande method presents a high dispersion of the results due to the influence of the operator and the conditions of the apparatus used to conduct this analysis (Sousa, 2011; Di Matteo, 2012; Mishra et al., 2012; Bicalho et al., 2017). Sowers et al. (1960) mention other limitations of the percussion method, such as the difficulty of making the classic groove in sandy clay soils and the fact that low plasticity soils tend to liquefy before flowing by plasticity. The LL_c (Liquid Limit determined by the Casagrande Method) assumes that the undrained shear strength (S_u) of the soils at the liquid limit has a constant value (about 2.5 kPa). However, the value of S_u at the liquid limit state can vary from 0.5 to 5.6 kPa (Whyte, 1982; Wasti and Bezirci, 1986).

The fall cone method for determining the Liquid Limit (LL_p), is defined in this article as the cone method. The method, developed by Hansbo (1957), measures the static penetration that a standardized cone under certain specified conditions of weight, angle, and fall time penetrates vertically into a previously prepared soil specimen. The LL_p is expressed by the water content corresponding to the penetration of 10, 17, 20, or 25 mm, depending on the country of origin, for the various weights and geometries of the cone. For example, the British cone specifies a penetration value of 20 mm, whereas, the Swedish cone specifies a penetration value of 10 mm for the LL_p of the soil. However, different depths produce different LL_p results. The cone method, not commonly used in Brazil, is an attractive alternative to the dynamic method of Casagrande (1932).

Additionally, the cone method consists essentially in evaluating the shear strength of the soil, based on the work of Hansbo (1957), which related the penetration depth of a cone of falling weight with the non-shear force drained from the soil. The LL_p result has less influence on the equipment and the execution in relation to the LL_c result, and in most places the British standard (30°, 80 g, 20 mm) is used, corresponding to an undrained shear force of about 1.7 kPa (O'Kelly et al., 2018).

The extensive database available with correlations between LL_c values and different engineering properties motivates the study of comparisons between LL_c and LL_p values. In addition, classical fine soil classification systems use LL_c values (Bicalho et al., 2017). The correlations between LL_c and LL_p vary according to the cone type (and depth of penetration) and hardness of the base of the used Casagrande apparatus. Özer (2009) mentions that in the percussion method with soft base, it is necessary to apply a greater number of strokes to close the groove of the soil specimen because more energy will be absorbed by the base. Although there are two main types of LL_c determination devices (i.e., with hard bases and with soft bases), the specifications for these two types of devices are not well defined in most existing standards.

Previous publications have shown that S_u at the liquid limit state decreases with the increase of the LL (Leflaive, 1971; Youssef et al., 1995; Leroueil and Le Bihan, 1996).

Thus, it can be seen that (Leroueil and Le Bihan, 1996): $LL_c<LL_p$, for $LL<LL_t$ [value that defines the transition between the low LL and high LL values is not well defined in literature (Bicalho et al., 2017)] and $LL_c>LL_p$, for $LL<LL_t$.

Kaolinite and smectite clays have different mechanisms that control the value of the liquid limit of these clays (Sridharan and Prakash, 2000): the LL of a smectite clay is mainly controlled by the presence of the adhesive water layer present in the clay mineral, while the kaolinite LL is mainly controlled by the forces between the particles of the clay mineral (for example, microstructure). Thus, in this article the correlations between LL_c (with hard base and soft base devices) and LL_p, for clays of different mineralogical compositions and LL values, are presented and discussed.

MATERIALS AND METHODS

In order to evaluate the correlations between the liquid limit values determined by the Casagrande or percussion (LL_c) and cone (LL_p) methods, the experimental data from 12 publications were used, totaling the amount of data, n, equal to 184 (percussion and penetration).

This study evaluated the fall cone method suggested by the British standard BS 1377 (BSI, 1990), which consists of a cone of mass of 80 ± 0.05 g, cone angle of 30 ± 0.1°, and fall time of 5 ± 1 s over a molded sample of soil and obtaining the value of the penetration of the cone. The LL_p value is defined by the water content at which the cone penetrates 20 mm. This study evaluated the experimental data published by: Wasti (1987), Sridharan and Prakash (2000), Grabowska-Olszewska (2003), Deka et al. (2009), Sousa (2011), Di Matteo (2012), Mishra et al. (2012), Nagaraj et al. (2012), Spagnoli (2012), Verástegui-Flores and Di Emidio (2014), Quintela et al. (2014), and Bicalho et al. (2017).

The experimental results of the LL_c determination, that is, by the percussion method, were initially separated according to the base hardness of the Casagrande apparatus in two groups: B-01 (Casagrande apparatus hard base, $LL_{c\text{-hard base}}$) and B-02 (Casagrande apparatus soft base, $LL_{c\text{-soft base}}$).

The references, mineral composition, and number of specimens (n) of the soils investigated in group B-01 (LL_p and $LL_{c\text{-hard base}}$) are presented in table 1. The results of the data evaluated in group B-01 are shown in figure 1. Verástegui-Flores and Di Emidio (2014) present experimental results for pure kaolinite clays and mixtures of bentonites and kaolinites. Therefore, the data are presented separately in table 1, by the mineralogy of the tested

Table 1. Summary of publications, mineral composition, and number of Specimens (n) of the soils investigated in group B-01 (LL_p and $LL_{c\text{-hard base}}$) with a total of 117 tested soil specimens

Reference	Mineral composition	Number of soil specimens
Wasti (1987)	Bentonites and natural soils mixture	10
Deka et al. (2009)	Smectites	10
Di Matteo (2012)	Kaolinite	6
Mishra et al. (2012)	Bentonite mixtures	12
Spagnoli (2012)	Kaolinite and illite	50
Verástegui-Flores and Di Emidio (2014)	Kaolinite	1
	Bentonite and kaolinite mixtures	5
Quintela et al. (2014)	Kaolinites and illites	14
Bicalho et al. (2017)	Local natural clay (Vitória - ES - Brazil), kaolinite	5
	Bentonite and fine sand mixtures	4

soils. The experimental results published by Bicalho et al. (2017) are also separated in table 1 considering the mineralogical composition of the tested soils (kaolinite natural clays and artificial mixtures of bentonites and sands).

The references, mineral composition, and number of specimens (n) of the soils investigated in group named B-02 (67 samples tested) are listed in table 2. The results of the data evaluated in B-02 are presented in figure 2. Sridharan and Prakash (2000) present experimental results obtained on pure kaolinite clays, smectites, and mixtures of bentonites and sands. Therefore, the data are presented separately in table 2, considering the mineralogy of the soils tested. The results published by Grabowska-Olszewska (2003) and Nagaraj et al. (2012) are also presented separately in table 2. The first publication presented experimental results on natural kaolinites and mixtures of bentonites and kaolinites and the second publication presented results of LL determined in natural kaolinites and smectites.

For each group of data (B-01 and B-02), two subgroups were defined to evaluate the correlations: kaolinites and illites (B-01i and B-02i) and smectites (B-01ii and B-02ii). The

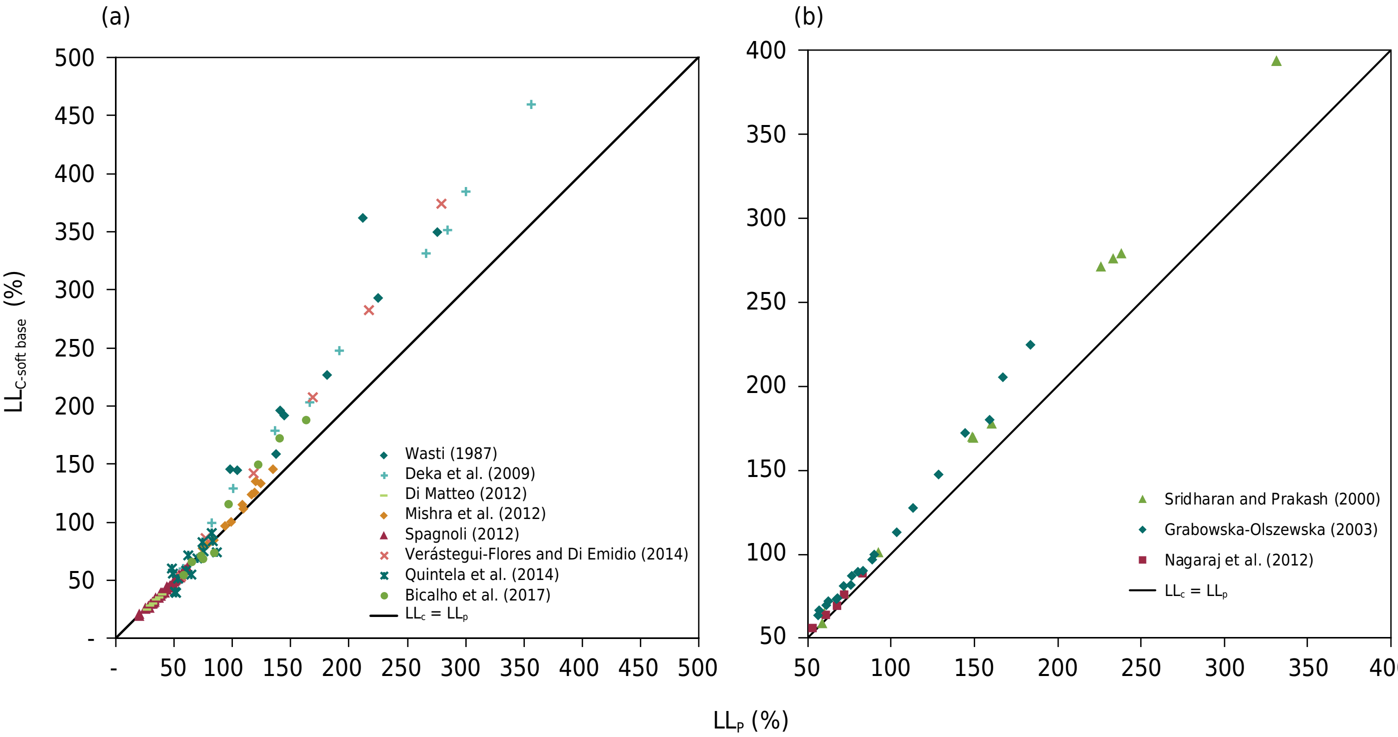

Figure 1. Experimental results: investigated soils in group B-01 (LL_p-$LL_{c\text{-hard base}}$), n = 117 (a); soils investigated in group B-02 (LL_p-$LL_{c\text{-soft base}}$), n = 67 (b).

Table 2. Summary of publications, mineral composition, and number of Specimens (n) of the soils investigated in group B-02 (LL_p and $LL_{c\text{-soft base}}$) with a total of 67 tested soil specimens

Reference	Mineral composition	Number of soil specimens
Sridharan and Prakash (2000)	Kaolinites	5
	Smectites and mixtures of sand and bentonite	14
Grabowska-Olszewska (2003)	Kaolinites	2
	Bentonite and kaolinite mixtures	20
Sousa (2011)	Kaolinites and illites	16
Nagaraj et al. (2012)	Kaolinites	5
	Smectites	5

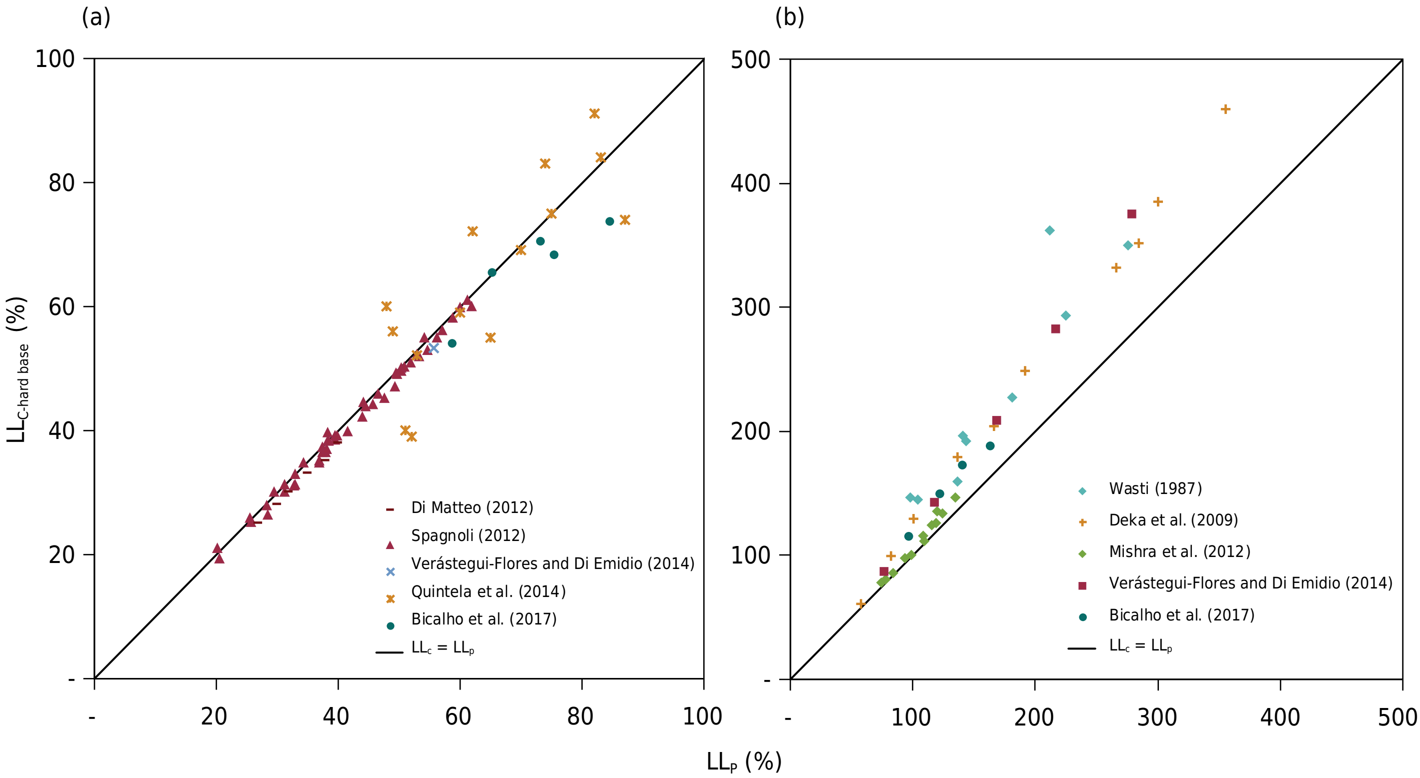

Figure 2. Experimental results (LL_p-$LL_{c\text{-hard base}}$) of the soils investigated in group B-01 in this research: subgroup B-01i with n = 76 formed essentially by kaolinites and illites (a); and subgroup B-01ii with n = 41 consisting essentially of smectites (b).

$LL_{c\text{-hard base}}$ and LL_p data pairs for each subgroup of data from group B-01 are presented in figure 2. Figure 2a shows the 76 pairs of $LL_{c\text{-hard base}}$ and LL_p data collected and grouped in the subgroup of data B-01i consisting of soils formed essentially by kaolinites and/or illites and published by Di Matteo (2012), Spagnoli (2012), Verástegui-Flores and Di Emidio (2014), Quintela et al. (2014), and Bicalho et al. (2017). In figure 2b, the 41 $LL_{c\text{-hard base}}$ pairs and LL_p of the data group B-01ii consisting of the soils formed essentially by smectites are reported and published by Wasti (1987), Deka et al. (2009), Mishra et al. (2012), Verástegui-Flores and Di Emidio (2014), and Bicalho et al. (2017). It can be seen in figure 2 that the transition between the low LL and the high LL values is about 80 %. That is, $LL_c<LL_p$ for $LL_c<80$ % and $LL_c>LL_p$ for $LL_c>80$ %, with a greater dispersion between LL_c and LL_p values for LL values >200 %.

Figure 3 shows the location of the soils investigated in group B-01 in the termed Plasticity or Casagrande chart with the classification proposed by the Unified Classification System (UCS) for fine-grained soils. Since the UCS uses the LL values determined by the Casagrande method, the LL results shown in figure 3 are the LL_c values. In figure 3a, where the results studied in the subgroup B-01i are presented, the relationship between the LL and PI of kaolinites studied by Di Matteo (2012) tends to converge into line A of the Casagrande chart, considered as the arbitrated division between silts and clays of the Casagrande chart. Line U means the approximate upper limit for natural soils and consists of a good verification of the existence of wrong data.

The experimental results of kaolinites, studied by Verástegui-Flores and Di Emidio (2014) and Bicalho et al. (2017), also tend to converge to the straight-line A of the Casagrande chart. The clays investigated by Quintela et al. (2014) predominate in the region of high plasticity dispersed around the A line of the Casagrande chart. It was not possible to plot the results of Spagnoli (2012) in figure 3a since the researcher did not indicate the plasticity index (PI) values for the investigated soil specimens.

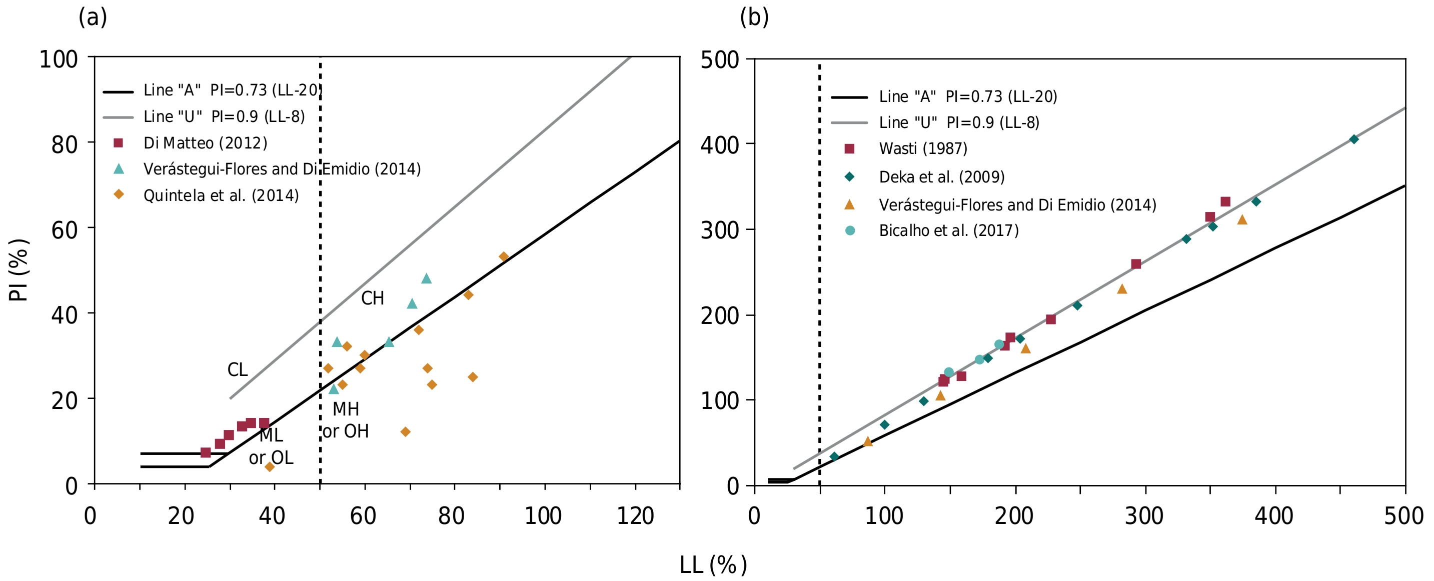

Figure 3. Location of the soils investigated in B-01i in the Casagrande chart (a) and location of the soils investigated in B-01ii in the Casagrande chart (b).

In figure 3b, which shows the location of the studied soils of B-01ii subgroup in the Casagrande chart, the relationship between the LL and PI of the bentonite mixtures studied by Wasti (1987) and Bicalho et al. (2017) tend to converge into the U line of the Casagrande chart. The experimental results of the bentonite mixtures studied by Verástegui-Flores and Di Emidio (2014) and the natural smectites studied by Deka et al. (2009) tend to converge into the U line of the Casagrande chart for higher LL values. The bentonite mixtures investigated by Mishra et al. (2012) were not presented in figure 3b because the researchers did not report the PI values of the investigated soil specimens.

The $LL_{c\text{-hard base}}$ and LL_p data pairs for each subgroup of data from group B-02 are presented in figure 4. Figure 4a shows 28 pairs of data collected and grouped in the subgroup of B-02i, consisting of soils that are formed essentially by kaolinites and/or illites and published by Sridharan and Prakash (2000), Grabowska-Olszewska (2003), Özer (2009), Sousa (2011), and Nagaraj et al. (2012). Figure 4b shows the 39 pairs of data collected and grouped in the subgroup of data B-02ii consisting of soils that are formed essentially by smectites and published by Sridharan and Prakash (2000), Grabowska-Olszewska (2003), and Nagaraj et al. (2012). It can be seen in figure 4 that the transition between the values considered from low LL and high LL is about 60 %. That is, $LL_c < LL_p$ for LL_c <60 % and $LL_c > LL_p$ for LL_c >60 %, with greater dispersion between LL_c and LL_p values for LL values >150 %.

Figure 5 shows the location of the soils investigated in group B-02 in the Casagrande chart. In figure 5a, the relationship between LL and PI of kaolinites and illites studied by Grabowska-Olszewska (2003), Sousa (2011), and Nagaraj et al. (2012) tend to converge into line A of the Casagrande chart. The experimental results of the kaolinites investigated by Sridharan and Prakash (2000) were not presented in figure 5a because the researchers did not mention the PI values for the investigated samples. In figure 5b, where the location of the soils studied in the subgroup B-02ii of the Casagrande chart is shown, the relationship between LL and PI of the mixtures of bentonites and kaolinites studied by Grabowska-Olszewska (2003) tend to converge into the A-line of the Casagrande chart. The experimental results of the smectites investigated by Nagaraj et al. (2012) also tend to converge into the straight A-line of the Casagrande chart, mainly for LL >100 %. The smectites and bentonites and sands mixtures investigated by Sridharan and Prakash (2000) were not plotted in figure 5b because the researchers did not indicate the PI values for the investigated soil samples.

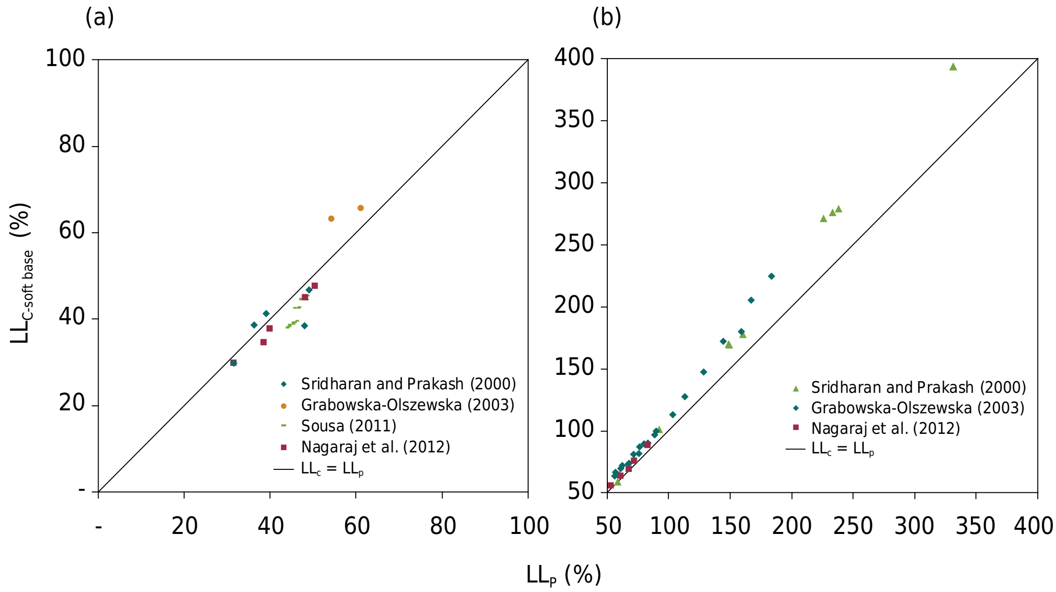

Figure 4. Experimental results (LL$_p$ – LL$_{c\text{-soft base}}$) of the soils investigated in group B-02 in this research: subgroup B-02i with n = 28 formed essentially by kaolinites and illites (a); and subgroup B-02ii with n = 39 consisting essentially of smectites (b).

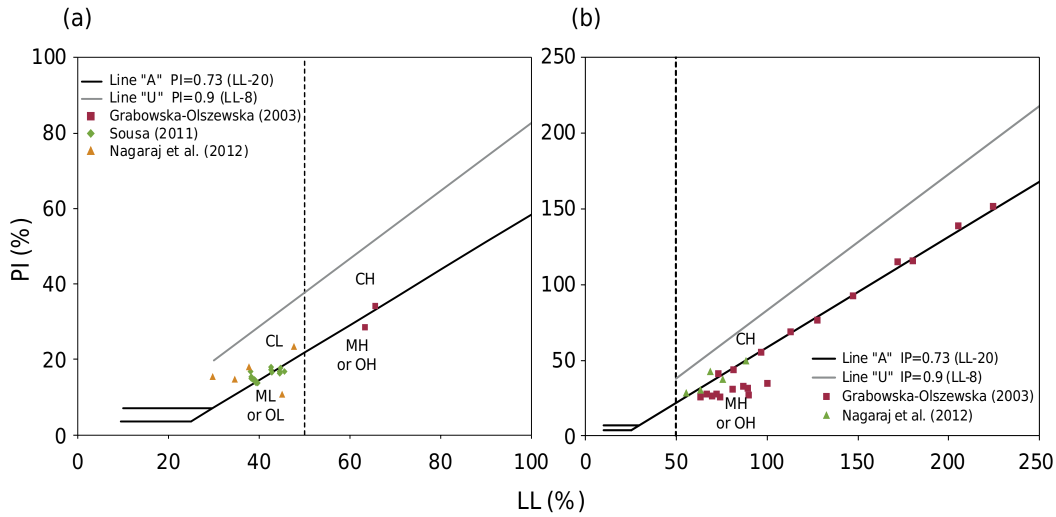

Figure 5. Location of the soils investigated in the B-02i in the Casagrande chart (a); and location of the soils investigated in B-02ii in the Casagrande chart (b).

RESULTS

The empirical correlations (i.e., LL$_{c\text{-hard base}}$ – LL$_p$ relationships) obtained for subgroups B-01i and B-01ii are given by equations 1 and 2, respectively. The equations were defined through linear regression with the respective determination coefficients (R^2). The number of soil specimens (n) and the range of LL$_c$ are indicated after the exclusion of outliers or atypical points.

B-01i: $LL_{c\text{-hard base}} = 1.0148\ LL_p - 1.366$ [n = 71, R^2 = 0.967; 20< LL$_c$ <100 %] Eq. 1

B-01ii: $LL_{c\text{-hard base}} = 1.352\ LL_p - 19.633$ [n = 39, R^2 = 0.984; 50< LL$_c$ <460 %] Eq. 2

Table 3 shows the statistical tests for equations 1 and 2 evaluated for B-01. The hypothesis tests (Tests F and t) evaluated for whether the regression parameters are significant in relation to the observed data, for which the p-value obtained should be lower than the 5 % significance. According Rodrigues (2012), the Kolmogorov Smirnov (KS test) or Shapiro Wilk (SW) adhesion tests for the sample evaluate whether the residues have a normal distribution if the p-value is greater than the 5 % significance. The Durbin Watson test (DW test) evaluates the independence between the residues and the analysis is done in the same way-through the p-value; if p-value > α (with a 95 % significance level), the residues are independent. It is observed in table 3 that, despite the high R^2 values of the correlations of group B-01, at least one of the statistical tests mentioned presented an unsatisfactory result for each evaluated correlation.

The empirical correlations obtained for the subgroups B-02i and B-02ii are given by equations 3 and 4, respectively. The equations were defined through linear regression, with the respective determination coefficients (R^2). The number of soil specimens and the range of LL_c are indicated after the exclusion of outliers or atypical points. The statistical tests for equations 3 and 4 evaluated for B-02 are listed in table 4. It can be observed that, despite the high R^2 value of equation 4, the statistical tests KS and DW presented an unsatisfactory result.

B-02i: $LL_{c\text{-soft base}} = 1.103\ LL_p - 7.601\ [n = 28, R^2 = 0.767; 30 < LL_c < 70\ \%]$ Eq. 3

B-02ii: $LL_{c\text{-soft base}} = 1.216\ LL_p - 8.834\ [n = 39, R^2 = 0.998; 50 < LL_c < 400\ \%]$ Eq. 4

Table 3. Summary of the results of the statistical tests for the correlations evaluated in B-01

Subgroup	Test	p value	Conclusion
B-01i	t (intercept)	0.227	Not satisfactory
	t (x)	2.00E-16	Satisfactory
	F	2.20E-16	Satisfactory
	KS	0.2759	Satisfactory
	DW	0.007712	Not satisfactory
B-01ii	t (intercept)	1.65E-04	Satisfactory
	t (x)	2.00E-16	Satisfactory
	F	2.200E-16	Satisfactory
	KS	3.15E-07	Not satisfactory
	DW	4.512-05	Not satisfactory

Table 4. Summary of the results of the statistical tests for the correlations evaluated in B-02

Subgroup	Test	p value	Conclusion
B-02i	t (intercept)	0.172	Not satisfactory
	t (x)	1.01E-09	Satisfactory
	F	1.01E-09	Satisfactory
	SW	0.01325	Not satisfactory
	DW	0.03681	Not satisfactory
B-02ii	t (intercept)	1.07E-08	Satisfactory
	t (x)	2.00E-16	Satisfactory
	F	2.20E-16	Satisfactory
	KS	0.000109	Not satisfactory
	DW	0.0287	Not satisfactory

DISCUSSION

The results of equations 1 and 2, presented in figure 6, showed the variation between LL_p and LL_c with a hard-base percussion apparatus by the mineralogy of the investigated soils. For clays with the mineralogical composition of essentially kaolinites and illites of different geological origins and LL_c values between 20 and 50 %, it is verified in figure 6a and in equation 1 that LL_p is up to 5.5 % greater than LL_c, that this difference decreases as LL increases, and that this trend is in agreement with the previous publications evaluated that used a hard base percussion apparatus and clays with the same mineralogical composition (Di Matteo, 2012; Spagnoli, 2012; Bicalho et al., 2017). The maximum variation observed between LL_c and LL_p in equation 1 (5.5 %) was close to the maximum correlation variation proposed by Spagnoli (2012) - that is, 4.5 %. The correlations proposed by Di Matteo (2012) and Bicalho et al. (2017) presented greater differences - that is, LL_p was greater than LL_c up to 12 and 15.5 %, respectively. For clays consisting essentially of smectites, with LL_c between 50 and 460 %, figure 6b and equation 2 showed LL_c results up to 30 % higher than LL_p, this difference being attenuated as LL decreases, and which is in agreement with the previous publications evaluated using a hard base percussion apparatus and for clays with the same mineralogical composition of Wasti (1987) and Mishra et al. (2012). In the correlation proposed by Bicalho et al. (2017), LL_c is greater than LL_p, but the difference between LL_c and LL_p increases as LL decreases. The maximum differences between LL_c and LL_p observed in the correlations proposed by Wasti (1987), Mishra et al. (2012), and Bicalho et al. (2017) are 59, 9.5, and 13 %, respectively.

Figure 7 shows the results of equations 3 and 4 evaluated for B-02 group. The results of equations for B-02 showed the variation between LL_p and LL_c with a soft base percussion apparatus by the mineralogy of the soils investigated. For clays with the mineralogical composition of essentially kaolinites and illites of different geological origins and values of LL_c between 30 and 70 %, it can be seen in figure 7a and in equation 3 that LL_p is higher than LL_c by up to 17 % for the investigated range of LL (30 to 70 %) and that the dispersion between the results decreases as LL increases. It is confirmed that this trend is in accordance with the correlation previously published by Budhu (1985), for which LL_p is greater than LL_c by up to 8 % for the same range investigated in B-02i. It is also verified that the trend of equation 3 is not in agreement with the previous publication

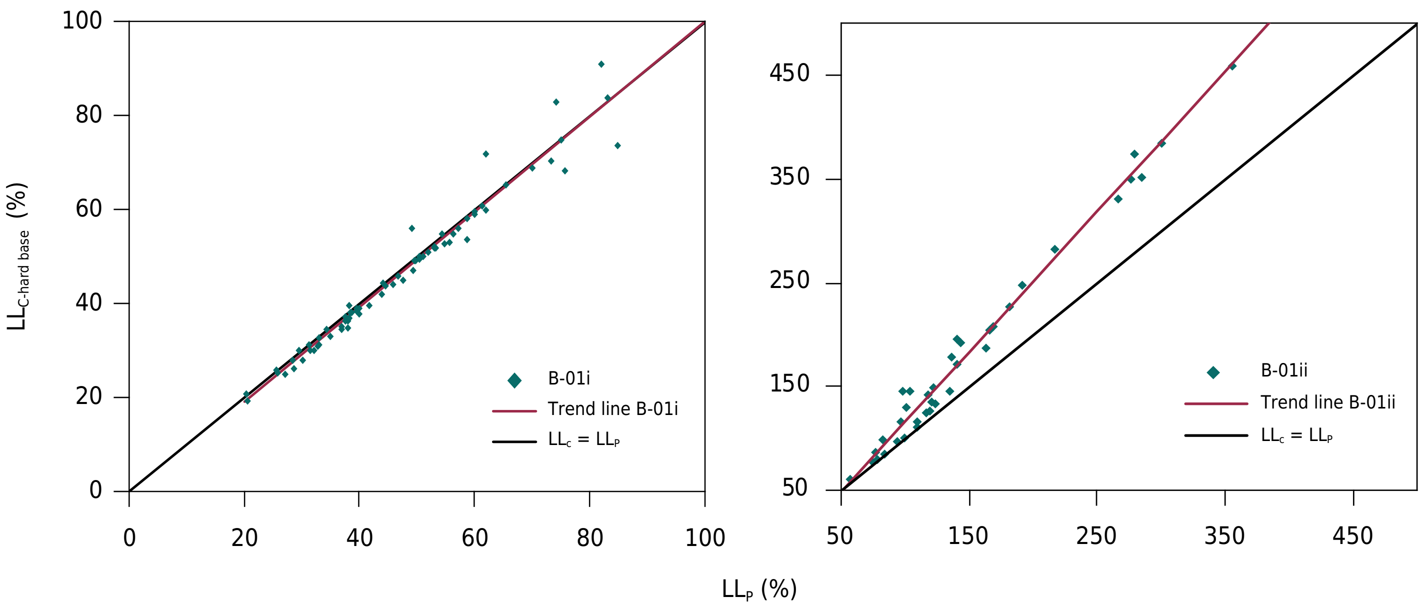

Figure 6. Trend lines of the experimental results, LL_p-$LL_{c\text{-hard base}}$, of the soils investigated in group B-01: subgroup B-01i (kaolinites and illites) with 20< LL_c <100 % (a); and subgroup B-01ii (smectites) with 50< LL_c <460 % (b).

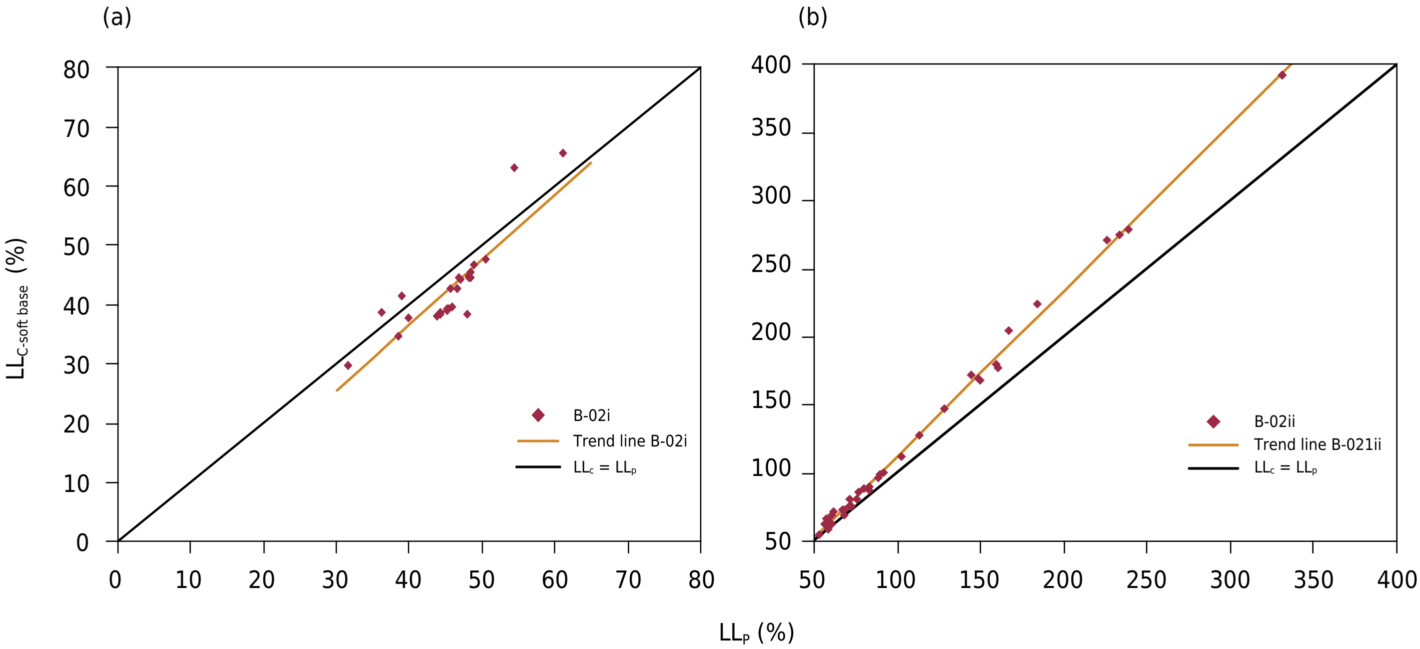

Figure 7. Trend lines of the experimental results, LL_p-$LL_{c\text{-soft base}}$, of the soils investigated in group B-02: subgroups B-02i (kaolinites and ilites) with 30< LL_c <50 % (a); and subgroups B-02ii (smectites) with 50< LL_c <400 % (b).

by Sousa (2011). As the R^2 of 0.767 of equation 3 does not represent a very strong correlation between the data observed and the statistical tests were unsatisfactory for most of the verifications, it is concluded that equation 3 is not valid. And it was not possible to determine, in this study, a correlation between LL_p and LL_c with a soft base percussion apparatus for clayey soils essentially formed by kaolinites and illites with LL values varying from 30 to 70 %. For clays consisting essentially of smectites, with LL_c values varying from 50 to 400 %, figure 7b and equation 4 showed LL_c results up to 19 % higher than LL_p, and that difference is attenuated as LL decreases. This trend is in accordance with the previous publication by Sridharan and Prakash (1998), defined for LL test results using a soft base Casagrande cup (i.e., $LL_{c\text{-soft base}}$) for kaolinites and smectites with the LL values ranging from 29 to 92 %.

The results of the correlations determined for $LL_{c\text{-hard base}}$ and $LL_{c\text{-soft base}}$ were compared in this study. Equation 2 defined for $LL_{c\text{-based hard}}$ and smectites showed a variation of values between LL_c and LL_p in the order of 10 % more than equation 4 defined for $LL_{c\text{-soft base}}$ for the same range of LL. Thus, the values of $LL_{c\text{-hard base}}$ are higher than the values of $LL_{c\text{-soft base}}$ for smectites. On the other hand, Özer (2009) and Haigh (2016) mentioned that the $LL_{c\text{-soft base}}$ values would always be larger than those $LL_{c\text{-hard base}}$ values. Özer (2009) and Haigh (2016) investigated the influence of the hardness of the base for liquid limits ranging up to 100 %. Therefore, the influence of base hardness should be further investigated for different mineralogies or ranges of LL values. It was not possible to compare the results of $LL_{c\text{-hard base}}$ and $LL_{c\text{-soft base}}$ between the correlations evaluated for kaolinites and illites (Equations 1 and 3) since equation 3 is not valid.

CONCLUSIONS

The LL_p and $LL_{c\text{-hard base}}$ data (i. e., group B-01) presented a difference of about 5 % between the LL_c and LL_p values for the kaolinites and illites, with LL_c values varying from 20 to 100 %. In addition, the results showed that LL_p is greater than LL_c. In group B-01 for smectites, with LL_c values varying from 50 to 460 %, LL_p is lower than LL_c and a large variation of measured LL_c and LL_p values was observed, with a difference of up to approximately 23 %. However, the LL_c-LL_p correlations evaluated in B-01 should be used with caution, since not all statistical tests were satisfactory, although the R^2 value indicates a very strong correlation between the data.

The evaluation of the B-02 correlations, that is, the results of LL_p and $LL_{c\text{-soft base}}$ indicated for kaolinites and illites, with a LL_c ranging from 30 to 70 %, found that the correlations are not valid due to the unsatisfactory results of most of the used statistical tests and the R^2 value. Similarly to the results obtained for B-01, smectites showed greater dispersion between measured LL_c and LL_p values in relation to kaolinites and illites, with a difference of up to approximately 19 %. However, the LL_c-LL_p relationship found in B-02 for smectites should be used with caution since the statistical tests of the residues were shown to be unsatisfactory, although the R^2 value indicates very strong correlation between the data.

Close examination of the influence of the hardness of the base of the Casagrande apparatus used in liquid limit tests (LL_c values) for smectites reveals that the linear correlation results showed higher values of LL_c for a harder base apparatus compared to a softer base apparatus. Therefore, it is necessary to investigate the influence of the base hardness on the LL_c-LL_p relationships for different mineralogies and ranges of LL values.

AUTHOR CONTRIBUTIONS

Conceptualization: Kátia Vanessa Bicalho.

Formal Analysis: Letícia Garcia Crevelin.

Methodology: Kátia Vanessa Bicalho.

Supervision: Kátia Vanessa Bicalho.

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REFERENCES

Andrade FA, Al-Qureshi HA, Hotza D. Measuring the plasticity of clays: a review. Appl Clay Sci. 2011;51:1-7. https://doi.org/10.1016/j.clay.2010.10.028

Bicalho KV, Gramelich JC, Cunha CLS, Sarmento Junior RG. Estudo dos valores do limite de liquidez obtidos pelos métodos de Casagrande e cone para diferentes argilas. Geotecnia. 2017;140:63-72. https://doi.org/10.24849/j.geot.2017.140.04

British Standards Institution - BSI. BS 1377: Methods of test for soil for civil engineering purposes. Part 2. Classification tests. Londres: British Standard Institution; 1990.

Budhu M. The effect of clay content on liquid limit from a fall cone and the British cup device. Geotech Test J. 1985;8:91-5. https://doi.org/10.1520/GTJ10515J

Casagrande A. Research on the Atterberg limits of soils. Public Roads. 1932;13:121-36

Deka S, Sreedeep S, Dash SK. Re-evaluation of laboratory cone penetration method for high liquid limit based on free swell property of soil. Geotech Test J. 2009;32:553-8. https://doi.org/10.1520/GTJ102205

Di Matteo L. Liquid limit of low- to medium-plasticity soils: comparison between Casagrande cup and cone penetrometer test. Bull Eng Geol Environ. 2012;71:79-85. https://doi.org/10.1007/s10064-011-0412-5

Grabowska-Olszewska B. Modelling physical properties of mixtures of clays: example of a two-component mixture of kaolinite and montmorillonite. Appl Clay Sci. 2003;22:251-9. https://doi.org/10.1016/S0169-1317(03)00078-4

Haigh SK. Consistency of the Casagrande liquid limit test. Geotech Test J. 2016;39:13-9. https://doi.org/10.1520/GTJ20150093

Hansbo S. A new approach to the determination of the shear strength of clay by the fall-cone test. Proceedings of the Royal Swedish Geotechnical Institute. 1957;14:7-47.

Leflaive E. Les limites d'Atterberg et le pénétromètre à cone. Bulletin de Liaison des Laboratories des Ponts de Chaussées. 1971;50:123-31.

Leroueil S, Le Bihan J-P. Liquid limits and fall cones. Can Geotech J. 1996;33:793-8. https://doi.org/10.1139/t96-104-324

Mishra AK, Ohtsubo M, Li LY, Higashi T. Influence of various factors on the difference in the liquid limit values determined by Casagrande's and fall cone method. Environ Earth Sci. 2012;65:21-7. https://doi.org/10.1007/s12665-011-1061-5

Nagaraj HB, Sridharan A, Madhu BV. Comparative study of determination of liquid limit by percussion cup, cone and K_0-stress methods. In: 8th International Symposium on Lowland Technology; September 11-13; 2012; Bali. Bali: Conference: International Seminar on LowLand Technology; 2012. p. 66-74.

O'Kelly BCO, Vardanega PJ, Haigh SK. Use of fall cones to determine Atterberg limits: a review. Geotechnique. 2018;68:843-56. https://doi.org/10.1680/jgeot.17.r.039

Özer M. Comparison of liquid limit values determined using the hard and soft base Casagrande apparatus and the cone penetrometer. Bull Eng Geol Environ. 2009;68:289-96. https://doi.org/10.1007/s10064-009-0191-4

Quintela A, Costa C, Terroso D, Rocha F. Liquid limit determination of clayey material by Casagrande method, fall cone test and EBS parameter. Mater Technol. 2014;29:B82-7. https://doi.org/10.1179/1753555714Y.0000000153

Rodrigues SCA. Modelo de regressão linear e suas aplicações [dissertação]. Covilhã: Universidade da Beira Interior; 2012.

Sousa PMLP. Limite de liquidez - correlações e comparações entre os métodos de *fall cone* e da concha de Casagrande [dissertação]. Lisboa: Universidade Nova de Lisboa; 2011.

Sowers GF, Vesic A, Grandolfi M. Penetration test of liquid limit. In: Papers on soils 1959 Meetings. Philadelphia: American Society for Testing Materials; 1960. p. 216-24. (ASTM Special Tecnical Publication, 254).

Spagnoli G. Comparison between Casagrande and drop-cone methods to calculate liquid limit for pure clay. Can J Soil Sci. 2012;92:859-64. https://doi.org/10.4141/CJSS2012-011

Sridharan A, Prakash K. Percussion and cone methods of determining the liquid limit of soils: controlling mechanisms. Geotech Test J. 2000;23:236-44. https://doi.org/10.1520/GTJ11048J

Sridharan A, Prakash K. Liquid limit and fall cone: discussion. Can Geotech J. 1998;35:407-8. https://doi.org/10.1139/t98-004

Verástegui-Flores RD, Di Emidio G. Assessment of clay consistency through conventional methods and indirect extrusion tests. Appl Clay Sci. 2014;101:632-6. https://doi.org/10.1016/j.clay.2014.09.033

Youssef MS, El Ramli AH, El Demery M. Relationships between shear strength, consolidation, liquid limit and plastic limit for remolded clays. In: 6th International Conference on Soil Mechanics and Foundation Engineering; September 1995; Montreal. Montreal: University of Toronto Press; 1995. p. 126-9.

Wasti Y. Liquid and plastic limits as determined from the fall cone and the Casagrande methods. Geotech Test J. 1987;10:26-30. https://doi.org/10.1520/GTJ10135J

Wasti Y, Bezirci MH. Determination of the consistency limits of soils by the fall-cone test. Can Geotech J. 1986;23:241-6. https://doi.org/10.1139/t86-033

Whyte IL. Soil plasticity and strength: a new approach using extrusion. Ground Eng. 1982;15:16-24.