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ORIGINAL PAPER

LIQUID LIMIT DETERMINATION OF MEDIUM TO HIGH PLASTICITY ALGERIAN SOILS USING FALL-CONE VS CASAGRANDE PERCUSSION CUP METHODS

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ABSTRACT

Determining the liquid limit (LL) of fine-grained soils is crucial in geotechnical site investigations. For a long time, the Casagrande Percussion Cup (CPC) test has been the standard method for this purpose. Although the Fall Cone Test (FCT) provides more repeatable results compared to the CPC test, its utilization remains limited in Algeria. To assess the effectiveness of the FCT, a comparative study was conducted using mixtures of bentonite and natural soils from Algeria. The choice of bentonite as an additive to soils with low plasticity is in order to formulate new samples with a wide range of plasticity. Our results showed that the LL_{CONE} values slightly exceeded the LL_{CUP} values for natural soil samples with medium plasticity. However, for soils with high and extreme plasticity, the LL_{CONE} values significantly underestimated the LL_{CUP} values. To address this issue, an equation was developed to convert LL_{CONE} measurements to LL_{CUP} values. This equation is consistent with previous literature and could help promote the adoption of the FCT method for geotechnical site investigations in Algeria.

1. INTRODUCTION

Soil water content has a significant impact on various engineering properties, such as shear strength, compressibility, swelling, permeability, cation exchange capacity, and specific surface area (e.g. Skempton,1944; Farrar and Coleman, 1967; Wroth and Wood, 1978; Muhunthan, 1991; Christidis, 1998; Sivapullaiah et al., 2000; Dolinar, 2009; Mehta and Sachan, 2017). By considering the water content and Atterberg limits, soil behavior can be well understood and predicted under different force conditions (Niazi et al., 2020). Atterberg (Atterberg, 1911a, b) initially proposed seven limits to describe changes in cohesive soil properties with water content. However, the LL, plastic limit (PL), and shrinkage limit (SL) are the most commonly used.

Atterberg introduced the technique for determining LL, which required counting the blows necessary to collapse a groove in a clay bed by striking the soil container against the hand (Atterberg, 1911a, 1911b). However, this method faced challenges due to its lack of standardization and repeatability issues. However, all credit must go to Casagrande, who designed the CPC; device featuring a sturdy plastic base and a flat grooving tool. Simultaneously, he defined the LL as the water content at which a soil paste requires 25 drops to close a groove measuring 12.5 mm in length (Casagrande, 1932, 1958). This modification for the CPC device is specified in various institutions and standards organizations in different countries to determine the LL. For example, it is specified in AASHTO T89-07 (2007) and ASTM D4318–17 (2017) in the USA, by BS 1377-2 (1990) in the United Kingdom, by EN ISO 17892-12 (2018) in the European Union, and by JGS 0142 (2000) in Japan. Other modifications, such as the motorized CPC with a drive assembly and geared blow counter (Niazi et al., 2020), have also followed this approach.

The CPC has been a commonly used method in geotechnical engineering. However, it has several limitations and potential inaccuracies. These include the need for subjective judgment when determining groove closure length, sensitivity to variations in apparatus adjustment techniques, difficulties in maintaining the apparatus, challenges in achieving repeatability, the impact of the cup and base stiffness on results, frequency of drop, wear of the grooving tool, and difficulties in cutting grooves in certain soil types (Wroth and Wood, 1978; Wasti and Bezirci, 1986; Özer, 2009; Spagnoli, 2012; Haigh, 2012, 2016; El-Shinawi, 2017; Crevelin, 2019). To address these issues, many researchers proposed the fall cone test (FCT) to determine the LL (e.g. Di Matteo, 2012; Crevelin and Bicalho, 2019; Wires, 1984).

The FCT was first developed by John Olsson in Sweden in 1915 to evaluate the undrained shear

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Table 1 Specifications and standards for FCT.

Countries	**U K** **Australia** **New Zealand** **India** **France**	**International**		**Sweden** **Norway** **Canada** **Japan**	**Russia** **Bulgaria** **China**
Standards	BSI 1377-2 AS 1289 NZS 4402 IS 2720 NFP94-052-1	ISO 17892-12		SS 027120 NS 8002 CAN/BNQ2501-092- JGS0142-	GOST 5180:84 BDS 648:1984 SD 128-007-84
Mass of cone (g)	80	80	60	60	76
Cone apex angle (°)	30 (30,5 India)	30	60	60	30
Penetration at LL (mm)	20 (17 France)	20	10	10 (11,5 Japan)	10 (17 China)

Source: (Kang et al., 2017; Ruge et al., 2020; Shimobe and Spagnoli, 2019a)

strength (Su) of clay soils (Hansbo, 1957). Over time, the FCT has become standardized for determining the LL of soils in numerous countries worldwide (refer to Table 1). Diverse setups for the FC apparatus are presented in Table 1. However, the British and Swedish cones are the most commonly employed. The British cone features an apex angle and weight of (30°, 80 g), while the Swedish cone has (60°, 60 g). The LL corresponds to a penetration depth of 20 mm for the British cone and 10 mm for the Swedish cone.

European nations such as the UK, Sweden, and Norway advocate for the FCT over the CPC test for LL determination (Di Matteo, 2012; Kang et al., 2017; Niazi et al., 2020; Díaz et al., 2021). In contrast, the American Society for Testing and Materials (ASTM D 4318, 2000) has adopted the CPC test.

The FCT method has improved the determination of LL in comparison to the CPC method in several ways. It offers easier maintenance and adjustment, simpler test conduction, more consistent results, lower sensitivity to equipment manufacturing differences, decreased reliance on operator skills, the ability to determine LL for low plasticity soils, and the potential to interpret soil shear strength near its LL (Casagrande, 1958; Sherwood and Ryley, 1970; Wasti and Bezirci, 1986; Koumoto and Houlsby, 2001; Cabalar and Mustafa, 2015; O'Kelly et al., 2018). Despite its advantages, several limitations of the FCT have been observed by many researchers. These include sensitivity to variations in equipment manufacturing, the influence of testing procedures on results rather than the soil's behavioral response, similar testing and analysis time compared to the CPC method, and significant differences between LLCONE and LLCUP values for high plasticity soils (Christaras, 1991; El-Shinawi, 2017; Grønbech et al., 2011; Hrubesova et al., 2020; Paute and Raskine, 1968; Sherwood and Ryley, 1970). Section 3 of the results and discussion should provide further details about the variation in LL values determined by both FCT and CPC methods.

2. MATERIALS AND METHODS

2.1. MATERIAL PRESENTATION

For this study, samples of bentonite (B) and three natural soils were used: grey clay (GC), yellow clay (YC), and white clay (WC). The B was selected for its high plasticity compared to the low to medium plasticity of the natural soils. These samples were obtained from quarries located in Tlemcen and Medea, which are situated in the northwest and north-middle regions of Algeria, respectively. The B powder is produced only in Tlemcen, while the three natural soils were procured from nearby locations chosen due to their geographical proximity. ENOF Company produced the B in powder form by extracting, crushing, grinding, and screening blocks from the Boughrara quarry in Maghnia, Tlemcen. Samples of the three natural soils were collected from a brick and tile quarry (GC and YC) and project excavation (WC) located in Medea. These samples were then treated in the laboratory of Numerical and Experimental Investigations in Geotechnical Engineering (NEIGE) at the University of Blida1, Algeria.

The natural soil samples of GC, YC, and WC were obtained in large solid blocks with varying compositions, unlike the homogeneous powdered form of B. To ensure homogeneity of the samples, pre-treatment procedures such as wet sieving, drying, grinding, and homogenizing were carried out on the three soil samples.

The chemical properties of the clays are summarized in Table.2. The B sample is mainly composed of silica (SiO_2) by (53.87 %) and alumina (Al_2O_3) by (19.82 %) with a ratio of SiO_2/Al_2O_3 of 2.72. Moreover, both of YC and GC are basically composed of almost similar chemical compositions, especially the SiO_2 and carbonate, as they extracted from the same site. However, the WC is mainly composed of carbonate by more than 80 %.

Table 3 presents the classification of tested clays' properties. It shows that WC, YC, and GC have moderate plasticity, while the B sample contains clay with extremely high plasticity and a PI of 179 %.

To define LLCONE, it is necessary to consider the weight and angle of the cone on one side, as well as the penetration depth on the other side, which varies between different standards.

Table 2 The chemical compositions of the tested samples.

Samples	SiO_2	Al_2O_3	Fe_2O_3	CO_2	CaO	Na_2O	K_2O	MgO	SO_3	TiO_2	Cl	Trace elements	Total
B	53.87	19.82	5.24	9.84	1.61	2.65	1.46	3.24	0.8	0.66	0.33	0.48	100
WC	10.94	5.16	2.01	33.32	47.1	0.04	0.21	0.57	0.09	0.31	0.01	0.24	100
YC	33.85	11.11	5.09	18.95	25.01	0.47	1.59	2.59	0.23	0.71	0.04	0.36	100
GC	32.53	10.61	4.82	18.88	26.93	0.54	1.5	2.31	0.83	0.67	0.03	0.35	100

Table 3 Physical properties of the tested samples.

Sample	LL_{CUP}(01)	PL(02)	PI(3)	Classification(04)	Granulometric analysis(05)		
					Clay %	Silt %	Sand %
B	219	40	179	Very high plasticity clay	68	20	12
WC	45	29	16	Organic clay medium plasticity silt	38	37	25
YC	44	23	21	Medium plasticity clay	45	40	15
GC	40	21	19	Medium plasticity clay	38	45	17

The LL_{CUP} and PL values (01 and 02) were obtained using CPC and thread rolling techniques, adhering to the ISO 17892-12 (2018) standard. The PI value (03) was derived by subtracting PL from LL. Description (04), resulting from values (01, 02, and 03), signifies the classification of fine soils based on the plasticity chart endorsed by L.C.P.C (Laboratoire Centrale des Ponts et Chaussées). Values (05) pertain to the particle size distribution of samples determined through a combination of sieving and sedimentation, following the ISO 17892-4 (2018) guidelines.

2.2. METHODS

To obtain samples covering a wide range of LL values, a set of reconstituted mixtures was formulated by blending different proportions of highly plastic bentonite with three natural soils of medium plasticity. Nine (09) reconstituted soils were formulated with B clay by 25 %, 50 %, or 75 % of the total mixture mass of B-WC, B-YC, and B-GC as specified in Table 4. In total, thirteen samples including B, WC, YC, GC, and their nine binary B-based mixtures were examined in this study. Each dry powder was manually mixed until the components achieved a consistent color. Then, each sample was mixed with an appropriate amount of distilled water and left for approximately 24 hours to achieve an even moisture level throughout. The samples were then split into three portions to conduct PL, LL_{CUP}, and LL_{CONE} tests.

To ensure the accuracy and consistency of the results, all tests for LL and PL were repeated on the same samples by the same operator, using the same measuring method and laboratory conditions in a short period. The PL, LL_{CUP}, and LL_{CONE} values were measured using the thread rolling method, CPC, and FC devices respectively, following the international standard ISO 17892-12 (2018). While this standard recommends reporting the LL and PL values as whole numbers, for statistical purposes, this study reported the LL and PL values in decimals, as shown in Table 5.

3. RESULTS AND DISCUSSION

According to ISO 17892-12 (2018), a minimum of four data points was collected within the 15–35 mm range of cone penetration depth for the FCT using the British cone, and within the range of 15-35 blows for the CPC test. The moisture content corresponding to a cone penetration of 20 mm and 25 blows is employed to determine LL_{CONE} and LL_{CUP}, respectively. This determination is based on the two best-fit equations obtained through linear regression analysis using the method of least squares for two linear graphs: the first graph plots moisture contents against their respective penetration values, while the second one plots moisture contents against their corresponding logarithm of the number of blows (logNi). The coefficient of determination (R^2) is calculated using the method of least squares.

Table 4 Proportions of reconstituted soils.

Reconstituted soils	**Type and percentage of 1st component**	**Type and percentage of the 2nd component**	**Soil designation**
reconstituted soil 1	Bentonite 25 %	Yellow clay 75 %	B25-YC75
reconstituted soil 2	Bentonite 50 %	Yellow clay 50 %	B50- YC50
reconstituted soil 3	Bentonite 75 %	Yellow clay 25 %	B75- YC25
reconstituted soil 4	Bentonite 25 %	Grey clay 75 %	B25- GC75
reconstituted soil 5	Bentonite 50 %	Grey clay 50 %	B50- GC50
reconstituted soil 6	Bentonite 75 %	Grey clay 25 %	B75- GC25
reconstituted soil 7	Bentonite 25 %	White clay 75 %	B25-WC75
reconstituted soil 8	Bentonite 50 %	White clay 50 %	B50- WC50
reconstituted soil 9	Bentonite 75 %	White clay 25 %	B75- WC25

Table 5 Results of the liquid and plastic limits of the samples tested.

Soil Designation	FCT method		CPC method		Thread rolling method	Plasticity Index
	LL_{CONE} (%)	R^2	LL_{CUP} (%)	R^2	PL (%)	PI= LL_{CUP}-PL (%)
YC	45.08	0.984	43.00	0.973	19.55	23.45
B25-YC75	74.25	0.992	76.82	0.948	26.63	50.19
B50-YC50	120.76	0.991	129.80	0.872	32.77	97.03
B75-YC25	152.07	0.994	177.81	0.930	39.44	138.37
GC	42.05	0.998	39.72	0.970	18.36	21.36
B25-GC75	83.24	0.993	90.53	0.966	22.15	68.38
B50-GC50	117.56	0.997	124.88	0.893	29.00	95.88
B75-GC25	155.70	0.999	183.46	0.991	38.02	145.44
WC	45.20	0.996	43.95	0.961	29.62	14.33
B25-WC75	80.20	0.998	89.25	0.948	26.38	62.87
B50-WC50	126.55	0.996	138.90	0.936	34.75	104.15
B75-WC 25	152.44	0.988	177.79	0.987	35.59	142.20
B	184.06	0.996	219.29	0.980	46.01	173.28

Table 5 displays the information for 13 studied samples, including LL determined using both CPC and FC techniques, along with the (R^2) value for each sample's LL determination for each method, PL obtained through the thread rolling method, and IP calculated by subtracting PL from LL.

Based on Table 5, the (R^2) values using the CPC test ranges from 0.87 to 0.98. However, the (R^2) values are generally higher than 0.97 when using FCT. This suggests that the FCT provides more accurate and concentrated results compared to the CPC test. Additionally, the measured LL_{CUP} values for YC, GC, WC, and B samples are 43 %, 40 %, 44 %, and 219 %, respectively. It is noticeable that YC, GC, and WC samples exhibit medium plasticity, whereas the B sample has high plasticity due to the abundance of montmorillonite, a major component that can absorb and retain water. Comparing the LL values of medium plasticity soils, it is observed that the LL_{CONE} values are slightly higher than the LL_{CUP} values, with a difference of less than 6 %. Several researchers have noted that, at lower LL levels, the LL_{CUP} values tend to be slightly smaller than the LL_{CONE} values (Özer, 2009; Zentar et al., 2009; Crevelin and Bicalho, 2019; Niazi et al., 2020)

Notably, there are some differences in the results of CPC and FCT tests for soils with high plasticity. In these cases, LL_{CONE} tends to underestimate the LL_{CUP} values by about 16 %. This aligns with the findings of Prakash and Sridharan (2006), who noted that there are differences in behavior between medium-plasticity kaolinitic soils and high-plasticity montmorillonite soils. Specifically, LL values are consistently higher when using CPC instead of FCT. Furthermore, Haigh (Haigh, 2012) explained that the LL_{CUP} is related to a specific strength, which is a ratio of undrained strength (Su) to soil density, while the LL_{CONE} is related to undrained strength by Hansbo's formula (Hansbo 1957). The difference between LL_{CONE} and LL_{CUP} can be predicted based on the fact that the density at LL is lower for soils with high LL than for those with lower plasticity. This confirms the findings of Sowers et al. (1960), who also observed similar results. Further research has shown that the Su at the LL state tends to decrease with increasing LL state for high plasticity soils (Hrubesova et al., 2020; O'Kelly et al., 2022; Paute and Raskine, 1968; Sharma and Sridharan, 2018).

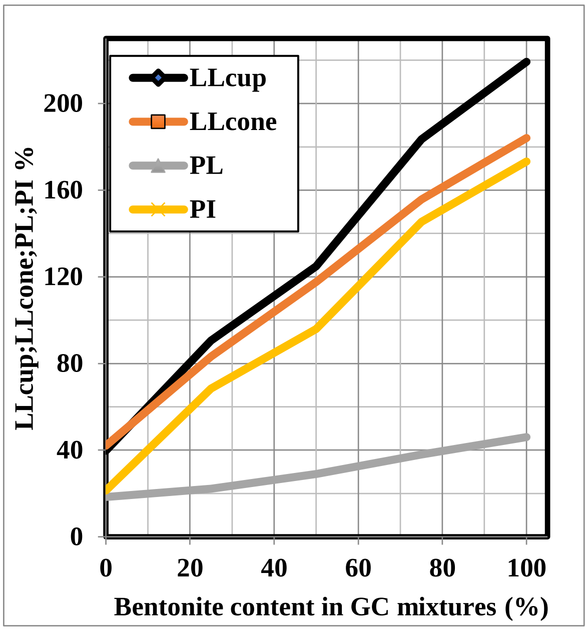
Using the data provided in Table 5, the analysis proceeds as follows: initially, examining the impact of bentonite content on the mixtures' LL, PL, and IP variations; secondly, exploring the correlation between LL_{CUP} and LL_{CONE}; and thirdly, comparing this correlation with previous observations.

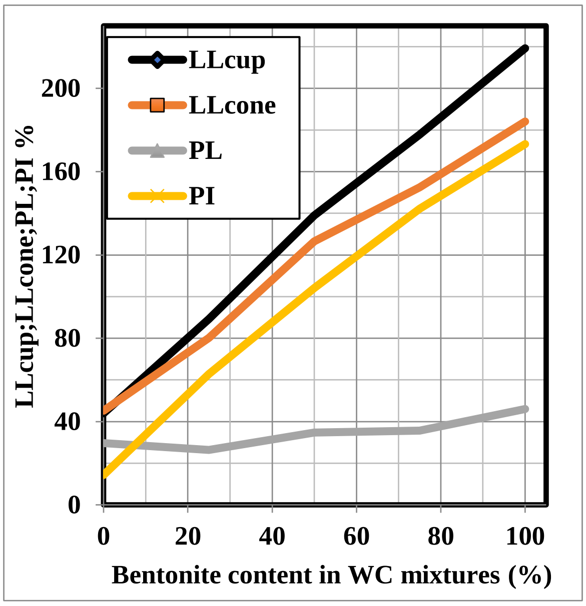
3.1. *EFFECT OF BENTONITE CONTENT ON LL, PL, AND PI*

Figure 1 showed the effect of bentonite content on LL, PL, PI parameters based on the results deduced from Table 5. The Y-axis represents the LL, PL, and PI values, while the X-axis shows the amount of B. The LL, PL, and PI values increase in direct proportion to the amount of B, and this relationship remains consistent. As the B content increases from 0 % (natural soil) to 100 % (pure bentonite), the LL, PL, and PI values increase approximately 5.5 times, 2 times, and 7 times, respectively. Therefore, it can be concluded that the mineralogical composition of clay soils affects the consistency parameters LL, PL, and PI. However, PL shows minimal variability compared to LL. This finding confirms the proposition of Spagnoli (2012), which showed that the influence of LL on PI is more significant than the impact of PL.

3.2. *CORRELATION BETWEEN LL_{CUP} AND LL_{CONE}*

This study utilized linear regression analysis to examine the correlation between LL_{CUP} and LL_{CONE} as primary variables, with LL_{CUP} being a more challenging measurement compared to the relatively simpler LL_{CONE}. As an alternative, this study used LL_{CONE} as an independent variable due to its ease of measurement and the added benefits of the FC device.





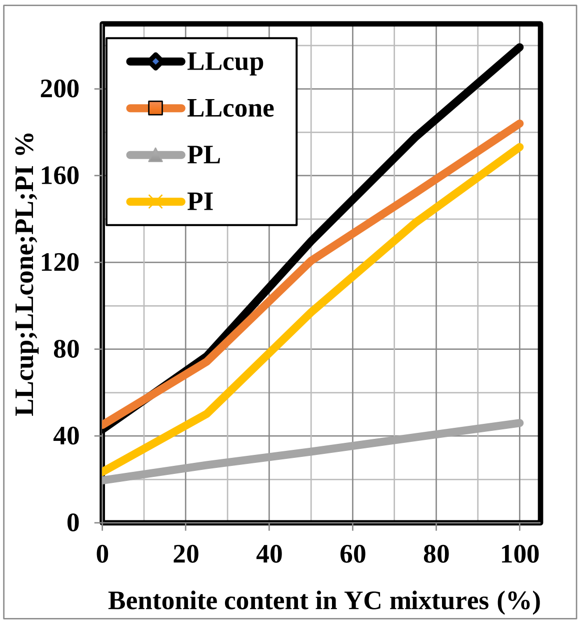


Fig. 1 Effect of bentonite content on LL, PL, PI parameters in Tested GC, YC, and WC Mixtures.

This approach differs from previous research, as evidenced in Table 6, where a linear equation in slope-intercept form was derived from LL_{CONE} = f (LL_{CUP}). Figure 2 displays the empirical relationship established through least squares linear regression analysis between LL_{CONE} values and their corresponding LL_{CUP}. The linear relationship between the variables can be represented by equation (a):

$$LL_{CUP} = 1.25 \times LL_{CONE} - 14.99 \quad \text{(a)}$$

Nonetheless, it's crucial to emphasize that this equation is specifically designed to forecast LL_{CUP} using LL_{CONE} values for soils across LL values ranging from 40 % to 219 %.

F.H. Kulhawy (Kulhawy and Mayne, 1990) pointed out that each regression is accompanied by key statistical metrics, including the number of data points (n), coefficient of determination (R^2), and standard error (SE) for the respective field test measurement. Equation (a) is presented with a coefficient of determination R^2=0.996, using a dataset consisting of n=13 points. Furthermore, it exhibits a standard error SE= 4.05 % and relative deviation RD=6.49, as depicted in Figure 2.

3.3. COMPARISON OF CASAGRANDE AND FCT LIQUID LIMIT BASED ON ACTUAL AND PREVIOUS RESEARCH

Tables 6 and 7 show case a compilation of 39 correlations between LL_{CUP} and LL_{CONE} sourced from the literature. The majority of these correlations (33), including the current correlation, utilize the British cone and are depicted in Table 6, while Table 7 illustrates six correlations obtained using the Swedish cone.

The presented information includes sources and references, locations of soil samples, sample counts, and the range of LL values. The most important aspect is the correlation established between two devices using the LL data.

Other investigators have suggested different correlations by employing various types of cones. Stefanoff (1957) and Tchacalova and Berov (2021) have respectively introduced correlations 1 and 2, utilizing the Vasiliev cone (30°, 76g, 10mm).

$$LL_{CONE} = 0.66 \times LL_{CUP} + 2.52 \quad \text{for } 30\,\% < LL < 50\,\% \quad (1)$$

$$LL_{CONE} = 0.69 \times LL_{CUP} + 5{,}1. \quad \text{for } LL < 150\,\% \quad (2)$$

Furthermore, Uppal and Aggarwal (1958) and Sivapullalah and Sridharan (1985) respectively presented correlations (3) and (4), employing the cone (31°, 148 g, 24.5 mm).

$$LL_{CONE} = 0.93 \times LL_{CUP} + 3.16 \quad \text{for } LL < 150\,\% \quad (3)$$

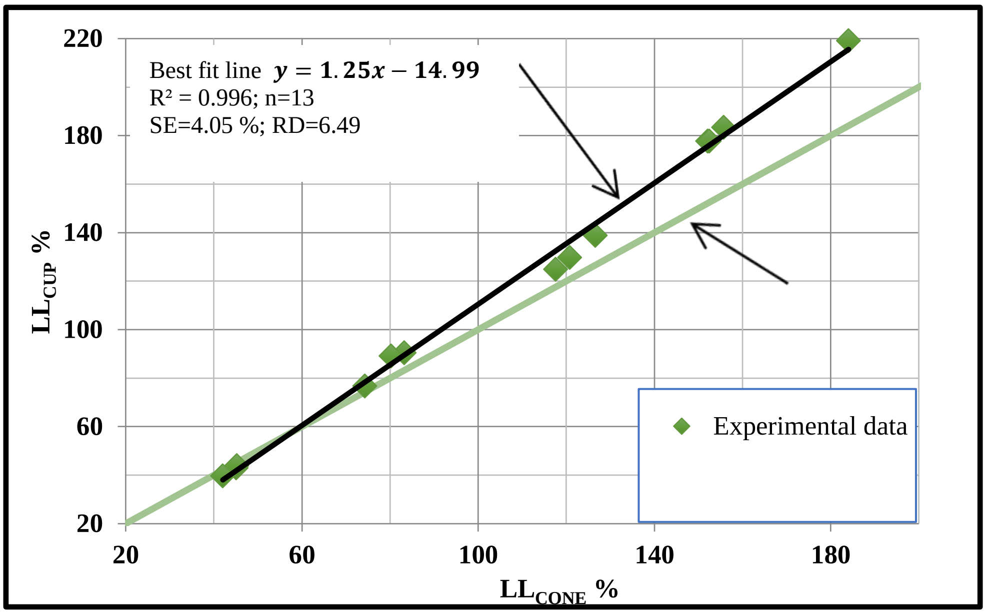


Fig. 2 Correlation between LL_{CUP} and LL_{CONE} using the 30°, 80 g cone (British cone).

$LL_{CONE} = 0.67 \times LL_{CUP} + 15.46$ for 37 %<LL<540 % (4)

For simplifying Figure 3 and facilitating comparisons of correlations utilizing the British cone, as employed in the present study, only the data from Table 6 are depicted on it. Figure 3 shows a strong correlation between LL_{CONE} and LL_{CUP} values within the LL_{CUP} range of 40 to 100 %. However, in soils with higher LL values, although the number of studies is limited, the CPC usually generates slightly higher LL values. This difference tends to magnify as LL values increase (i.e., >100 %), becoming notably pronounced in clay soils characterized by very high to extremely high plasticity. The correlation identified in this study aligns with the findings reported in references 15 (Zentar et al., 2009) and 32 (Crevelin and Bicalho, 2019).

4. CONCLUSION

The initial thought in this study was to investigate the LL values using both the CPC and FC devices and to derive a correlation between the two methods. LL_{CUP} and LL_{CONE} were investigated for different combinations of bentonite with three natural soil mixtures from the Medea and Tlemcen regions of northern Algeria. Based on the results obtained, the conclusions of this investigation are summarised as follows:

1. LL_{CONE} values for natural soil samples with medium plasticity reveal a slight increase over LL_{CUP} values (LL_{CUP} = 40-44 %). The ratio of LL_{CONE} to LL_{CUP} ranged between 1.03 and 1.06. Whereas, for samples with LL_{CUP} values ranging from 77 to 139 %, the same ratio ranged from 0.90 to 0.97. This deal to a good agreement between the two methods.
2. For samples with LL_{CUP} ranging from 178 to 219 %, the ratio is more pronounced, at between 0.84 and 0.86, which is consistent with previous studies.
3. The comparison of the proposed linear regression obtained between the LL_{CUP} and the LL_{CONE} with the results of previous researches shows a good agreement.
4. Due to its easy operation and repeatability, it is more convenient to use the FCT test to measure the liquidity limit.

This study highlights the need to widen the range of samples showing significant plasticity. This will lead to a more complete set of results and a more representative correlation.

NOMENCLATURE

B: bentonite from the Tlemcen region
CPC: Casagrande percussion cup
FCT: fall-cone test
GC: gray clay from the Medea region
LL: liquid limit
LL_{CONE}: liquid limit using fall-cone test
LL_{CUP}: liquid limit using CPC device
n: number of data points used to generate a regression
PL: plastic limit
R^2: coefficient of determination
RD: relative deviation
SE: standard error of a regression
SL: shrinkage limit
Su: undrained strength
w: water content
WC: white clay from the Medea region
YC: yellow clay from the Medea region

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Table 6 Equations correlating the LL_{CUP} and LL_{CONE} using the 30°,80 g cone (British cone).

Ref.N°	Authors	Empirical relationship	R^2	Range of LL (%)	Number of samples/ Location	Base of CPC
						Hard/Soft
01	Sowers et al. (1960)	$LL_{CONE}=0.79\times LL_{CUP}+8.39$	-	10-130	21 / USA	Hard
02	Sherwood and Ryley (1970)	$LL_{CONE}=0.95\times LL_{CUP}+0.95$	-	30-72	25 /England and Africa	Soft
03	Littelon and Farmilo (1977)	$LL_{CONE}=0.97\times LL_{CUP}+1.60$	-	20-450	19 / Worldwide places	Soft
04	Wires (1984)	$LL_{CONE}=0.94\times LL_{CUP}+0.97$		38-55	4 /Unavailable	Hard
05	Belviso et al. (1985)	$LL_{CONE}=0.99\times LL_{CUP}+4.29$	0.984	34-134	16 Italy	Hard
06	Sampson and Neterberg (1985)	$LL_{CONE}=1.01\times LL_{CUP}+4.20$	0.986	20-120	43 /SouthernAfrica	Hard
07	Wasti and Bezirci (1986)	$LL_{CONE}=1.01\times LL_{CUP}+4.92$	0.928	27-110	25 /Turkey	Hard
08	Campos et al. (1999)	$LL_{CONE}=0.88\times LL_{CUP}+8.13$	0.960	24-72	15 / Brazil	Hard
09	Feng (2001)	$LL_{CONE}=0.94\times LL_{CUP}+2.60$	-	25-76	66 / Worldwide places	Hard
10	Li (2004)	$LL_{CONE}=1.01\times LL_{CUP}+0.68$	-	30-455	19 / Taiwan	Hard
11	Orhan et al. (2006)	$LL_{CONE}=1.02\times LL_{CUP}+2.13$	-	27-98	16 /Turkey	Hard
12	Dragoni et al. (2008)	$LL_{CONE}=1.02\times LL_{CUP}+2.87$	0.980	28-74	41 / Italy	Hard
13	Özer (2009)	$LL_{CONE}=0.90\times LL_{CUP}+6.04$	0.996	29-104	32 /Turkey	Hard
14	Fojtová et al. (2009)	$LL_{CONE}=1.00\times LL_{CUP}+2.44$	0.978	20-51	52 /Czech	Hard
15	Zentar et al. (2009)	$LL_{20}=0.78\times LL_{CUP}+12.74$	0.992	38-130	14 / France	Unavailable
16	Zentar et al. (2009)	$LL_{17}=0.64\times LL_{CUP}+17.20$	0.980	38-130	14 / France	Unavailable
17	Spagnoli (2012)	$LL_{CONE}=0.99\times LL_{CUP}+1.05$	0.990	20-61	50 / Germany	Hard
18	Di Matteo (2012)	$LL_{CONE}=1.00\times LL_{CUP}+2.20$	0.980	24-40	6 /Italy	Hard
19	Cevallos Luna (2012)	$LL_{CONE}=1.12\times LL_{CUP}-6.31$	0.985	19-85	36 /Ecuador	Hard
20	(Mishra et al., 2012)	$LL_{CONE}=0.84\times LL_{CUP}+11.69$	0.992	77-135	12 / Japan	Hard
21	Silva (2013)	$LL_{CONE}=1.05\times LL_{CUP}+0.61$	-	38-45	10 / Portugal	Hard
22	Bicalho et al. (2014)	$LL_{CONE}=1.00\times LL_{CUP}+2.70$	0.980	14-98	42 / Brazil	Hard
23	Kayabali et al. (2016)	$LL_{CONE}=1.00\times LL_{CUP}+2.00$	0.990	28-166	275 /Turkey	Hard
24	Kollaros (2017)	$LL_{CONE}=1.03\times LL_{CUP}-4.93$	0.990	53-75	6 /Greece	Hard
25	El-Shinawi (2017)	$LL_{CONE}=0.91\times LL_{CUP}+5.64$	0.949	28-70	40 / Egypt	Hard
26	O'Kelly et al. (2018)	$LL_{CONE}=1.45\times LL_{CUP}^{0.92}$	0.970	17-108	188 /Worldwide places	Hard
27	Shimobe and Spagnoli (2019a)	$LL_{CONE}=0.95\times LL_{CUP}-0.85$	0.962	15-500	156 /Worldwide places	Soft
28	(Niazi et al., 2020)	$LL_{CONE}=0.89\times LL_{CUP}+4.20$	0.985	11-65	65 / USA	Hard
29	Crevelin (2019)	$LL_{CONE}=0.99\times LL_{CUP}+1.35$	0.967	20-100	71 /Worldwide places	Hard
30	Crevelin (2019)	$LL_{CONE}=0.74\times LL_{CUP}+14.54$	0.984	50-460	39 /Worldwide places	Hard
31	Crevelin (2019)	$LL_{CONE}=0.91\times LL_{CUP}+6.89$	0.767	30-70	28 /Worldwide places	Soft
32	Crevelin (2019)	$LL_{CONE}=0.82\times LL_{CUP}+7.27$	0.998	50-400	39 /Worldwide places	Soft
33	Present study	$LL_{CONE}=0.80\times LL_{CUP}+11.99$	0.99	40-219	13 / Algeria	Unavailable

Table 7 Equations correlating the LL_{CUP} & LL_{CONE} using the 60°,60g cone (Swedish cone).

Ref. N°	Authors	Empirical relationship	R^2	Range of LL (%)	Number of samples/Location	Base of CPC
						Hard/Soft
01	Karlsson (1961; 1977)	$LL_{CONE}=0.85\times LL_{CUP}+5.02$	-	30-76	91 /Sweden	Hard
02	Leroueil et al.(1983)	$LL_{CONE}=0.86\times LL_{CUP}+6.34$	-	30-74	43 / Canada	Hard
03	Mendoza and Orozco (2001)	$LL_{CONE}=0.85\times LL_{CUP}+7.10$	-	30-100	- / -	Hard
04	Mendoza and Orozco (2001)	$LL_{CONE}=0.77\times LL_{CUP}+10.71$	-	30-390	- / -	Hard
05	Grønbech et al. (2011)	$LL_{CONE}=0.95\times LL_{CUP}+9.40$	0.952	85-200	33 /Denmark	Hard
06	Claveau Mallet et al. (2012)	$LL_{CONE}=0.87\times LL_{CUP}+8.98$	-	50-70	9 / Canada	Hard

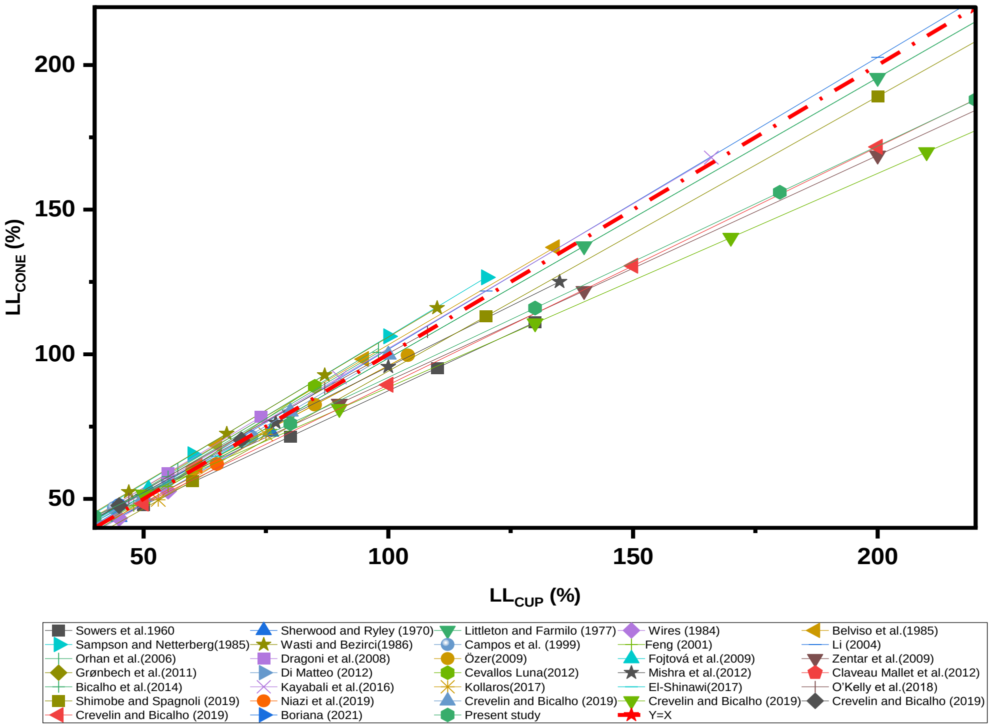

Fig. 3 Comparison of LL_{CONE} vs LL_{CUP} using 30°, 80g cone (British cone).

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