Periodica Polytechnica Civil Engineering, 69(3), pp. 772–785, 2025

Determination of Plastic Limit by Fall Cone Test for Soils with Different Grain Size Distribution

Murat Gulen[1*], Oguzhan Saltali[2], Havvanur Kilic[3]

[1] Department of Civil Engineering, Faculty of Engineering, Siirt University, University Street, 56100 Siirt, Türkiye
[2] Department of Civil and Environmental Engineering, Michigan State University, 428 S. Shaw Lane, MI 48824 East Lansing, Michigan, USA
[3] Faculty of Civil Engineering, Yildiz Technical University, Davutpasa Street, 34220 Istanbul, Türkiye
[*] Corresponding author, e-mail: murat.gulen@siirt.edu.tr

Received: 15 August 2024, Accepted: 24 March 2025, Published online: 14 April 2025

Abstract

Compaction parameters and consistency limits are fundamental engineering properties considered in the design of geotechnical applications. It is important to compare these parameters derived from experimental studies with the equations proposed in the literature or alternative methods. This study determined the plastic limit values of soils with different grain size distributions and different consistency limits using the relationship between penetration depth and water content from the fall cone test, employing a cone with 30° and 80 g characteristics. The method for determining the plastic limits has been developed based on a wide range of data. It defines the water content corresponding to a 3 mm penetration of the cone into the soil as the plastic limit. The plastic limit values determined by the proposed method were tested with a comprehensive dataset compiled from literature studies. The results indicated a satisfactory correlation between the plastic limits determined by the tread rolling method and those determined by the proposed method (R^2 = 0.76). Furthermore, the compaction parameters obtained from the standard compaction tests were investigated using univariate and multivariate regression analyses, with consideration given to the liquid and plastic limits determined from the fall cone tests. The findings indicate that the compaction parameters can be predicted with high coefficients of determination (R^2 = 0.89) using the plastic and liquid limits determined from the relationship between water content and penetration depth in the fall cone tests.

Keywords

modified plastic limit, fall cone test, penetration depth, water content, compaction parameters

1 Introduction

Soils with different grain size distributions and consistency limits are commonly utilised as backfill materials in geotechnical applications, including earth embankments, dams, road embankments, and solid waste storage facilities. The engineering properties of soils, including specific gravity (Gs), plastic limit (PL), liquid limit (LL), plasticity index (PI), maximum dry unit weight (MDW), optimum water content (OWC), undrained shear strength (Cu), sensitivity of clays (St), degree of saturation (Sr), grain size distributions, and mineralogy, are employed to assess the suitability of these soils.

The liquid limits of cohesive soils are mostly determined using the Casagrande apparatus developed by Casagrande [1] and known by its name, besides the fall cone device developed by Olsson [2]. According to some researchers, the fall cone liquid limit (LL_{FC}) value is more reliable and realistic than the Casagrande liquid limit (LL_{CUP}) value since the former is more independent of the tester than the latter [3–6]. Comparing the liquid limits determined from such tests, the LL is close to each other for the soils with LL less than 100%, while significant differences are observed between LL for the soils with LL greater than 100% [7–10].

According to the cone angle and weight, the LL_{FC} values determined using a fall cone with different properties and the penetration depth (h) corresponding to such LL_{FC} can differ as shown in Table 1 [11–20]. The fall cone features in Table 1 are defined by relevant standards, which are considered in literature studies. The penetration depth (h_L) of 10 mm is generally accepted for the LL_{FC} value from the fall

Cite this article as: Gulen, M., Saltali, O., Kilic, H. "Determination of Plastic Limit by Fall Cone Test for Soils with Different Grain Size Distribution", Periodica Polytechnica Civil Engineering, 69(3), pp. 772–785, 2025. https://doi.org/10.3311/PPci.38114

Table 1 The fall cone test standards of different countries

Cone properties					The relationship used during the interpretation	Cone penetration depth at the LL_{FC} (mm)
Reference	Country	Standard	Angle (°)	Mass (g)		
[11]	Sweden	SS 027120	60	60	log *h* – *w*	10
[12]	Norway	NS 8002	60	60	log *h* – *w*	10
[13]	Japan	JGS 0142	60	60	*h* – *w*	11.5
[14]	India	IS 2720-5	31	148	*h* – *w*	20
[15]	UK	BS 1377-2	30	80	*h* – *w*	20
[16]	New Zealand	NZS 4402	30	80	*h* – *w*	20
[17]	France	NF P 94-052-1	30	80	*h* – *w*	17
[18]	China	SL237-007	30	76	log *h* – log *w*	17
[19]	Russia	GOST 5184	30	76	*h* – *w*	10
[20]	Australia	AS 1289	30	80	*h* – *w*	20

cone having a cone 60° and 60 g configuration, whereas the h_L of 20 mm is commonly used for the LL_{FC} value of the fall cone with 30° and 80 g. Kumapley and Boakye [21] state that while the h_L value changes in the range of 10–12 mm in soils with LL less than 90% for a cone of 60° and 60 g, Japanese Geotechnical Society [22] expresses the h_L value as the water content (*w*) corresponding to 11.5 mm penetration. Two different methods determine the liquid limits of the soils, while the plastic limits are determined only by the tread rolling method. For this test, soil is mixed with water until it becomes plastic and easily molded into a ball. An 8–10 g sample is then rolled by hand on a glass plate until it crumbles at a 3.2 mm diameter. This process is repeated three times per sample, and the water content at crumbling is recorded as the PL. It should be noted that the plastic limits determined through the tread rolling method are highly dependent on the operator's experience. Thus, the PL value may exhibit variability when performed under identical conditions. This has led to the necessity of determining the PL using alternative methods. Several researchers have derived the PL value from the *w*-*h* relationship obtained from the fall cone test [23, 24].

Notedly, Wood and Wroth [24] indicated that if a single test determined the PL and LL values of soils, these values would be considerably easier, more useful, and more meaningful. In this context, they showed that the PL value can be calculated with empirical equations developed by the *h*. Koumoto and Houlsby [23] accepted the *w* value corresponding to 1.15 mm penetration depth as the PL for the fall cone having a cone of 60° and 60 g configuration. No penetration value corresponding to the PL value for the fall cone with the properties of 30° and 80 g has not been proposed in the literature.

The relationships between consistency limits and other engineering properties have been the focus of investigation by various researchers. One of the earliest studies to examine the relationship between compaction parameters and consistency properties was carried out by Jumikis [25]. Ring et al. [26] proposed equations for predicting MDW and OWC using the PL, LL, PI, median diameter (D_{50}), and fine content. Nagaraj et al. [3] determined the modified compaction parameters (MPP) and consistency limits using a total of 42 cohesive natural soils with grain sizes less than 0.425 mm and greater than 0.425 mm and having different consistency properties. It was suggested that the modified plastic limit (MPL) value could be calculated by considering the soils with grain sizes larger than 0.425 mm sizes larger than 0.425 mm, and they also made suggestions for determining the MPP values using the MPL value. Blotz et al. [4] and Gurtug and Sridharan [5] determined the compaction parameters of cohesive soils with different consistency properties by considering the PL, LL, and different compaction energy levels. When the studies on the estimation of compaction parameters using consistency limits are examined, three views are commonly employed on the topic. While Nagaraj et al. [3], Sridharan and Nagaraj [6], Sivrikaya et al. [7], and Jyothirmayi et al. [8] stated that the compaction parameters exhibited a better correlation with the PL value, Ng et al. [9], Saikia et al. [10], Gurtug et al. [27], Hussain and Atalar [28], and Fondjo et al. [29] underlined the compaction parameters exhibited a better correlation with the LL value. According to other researchers, employing the PL and LL values together resulted in a higher correlative relationship [30–33]. The compaction parameters are expressed as a function of PL, LL, PI, Gs, and grain size distributions. Thus, a comprehensive data set was constituted as a result of the studies in the literature. The data were evaluated using various multivariate analysis methods, including, regression analyses, SPSS, and artificial neural networks [7, 30–36].

This study developed a method that considers the relationship between *h* and *w* to determine the plastic limit value (PL_{FC}) for soils with different grain size distributions and consistency limits from the fall cone test with 30° and 80 g properties. The PL_{FC} values were tested using a comprehensive data set from the literature. Furthermore, the compaction parameters of soils with different grain diameter distributions were predicted by univariate and multivariate regression analyses utilising the PL_{FC} and LL_{FC} values obtained from a single test device. In particular, the compaction parameters for the PL_{FC} and LL_{FC} values can be determined based on the comparisons performed by examining an extensive database comprising 594 data resources.

2 Material and methods

A total of 83 natural cohesive soil samples with different index properties were supplied from various regions of Turkey (Kocaeli, Bilecik, Isparta, Karaman, Burdur, Trabzon, Tokat, and Erzincan), notably from Istanbul. The PL, LL, Gs, and grain size distribution of each soil sample were determined at the Yildiz Technical University Geotechnical Engineering Laboratory. Fig. 1 shows the plasticity chart of the soils in which the LL_{FC} values are in the range of 22.5% and 121.4%, determined by the fall cone with 30° and 80 g, the PL values between 16% and 63.5% by the thread rolling method and the PI values calculated as LL_{FC}-PL vary between 12.57% and 63.76% according to British Soil Classification System (BSCS).

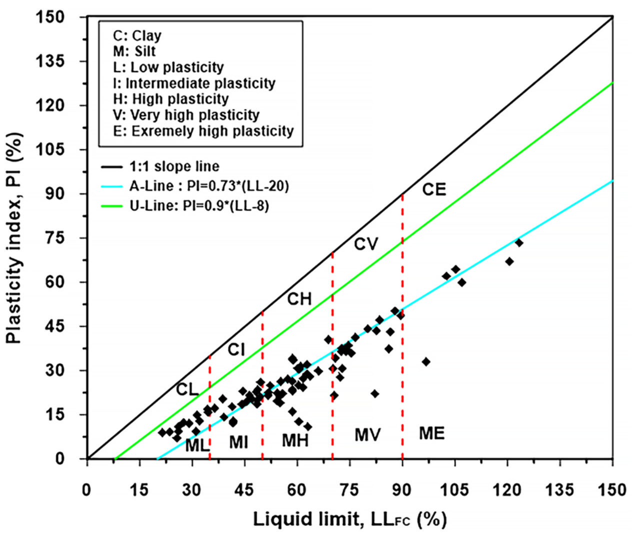


Fig. 1 Soils in the scope of this study

The classification distributions for these soils are presented by the following specifications: MI (5 soils), MH (19 soils), MV (16 soils), ME (4 soils), CL (12 soils), CI (12 soils), CH (9 soils), CV (4 soils), and CE (2 soils). As depicted in Fig. 2, the *h* ranged between 1.96 mm and 29.62 mm, and the *w* values were 7.56% and 135% in the fall cone tests performed at an average of 6 points for 83 cohesive soils with different consistency properties. Soil samples prepared with 6 different *w* values for each soil were kept in a humidity cabinet for 24 h. The samples were made more homogeneous by mixing at regular intervals for 24 h. Furthermore, it was ensured that at least three points of the *h* values obtained from the fall cone test, corresponding to the six distinct water contents, were situated between 15 and 25 mm.

In the present study, the PL_{FC} was determined by reference to the *w* and *h* relationship obtained from the fall cone tests and by the following steps (Fig. 3). Fig. 3 (a), the line that best fits these points on the double logarithmic axis was determined for six different *w* and *h* values for each soil. Following the:

- (1) process step, the 20 mm penetration value is extended with this slope line in the vertical direction. The value of this point on the y- axis is determined by following the LL_{FC},
- (2) process step. After determining the LL_{FC} value, the slope line drawn for 6 different *w* and *h* is extended to the y-axis by following the procedure step,
- (3) The PL value determined by the tread rolling method for each soil is extended to the trend line by following the process step,

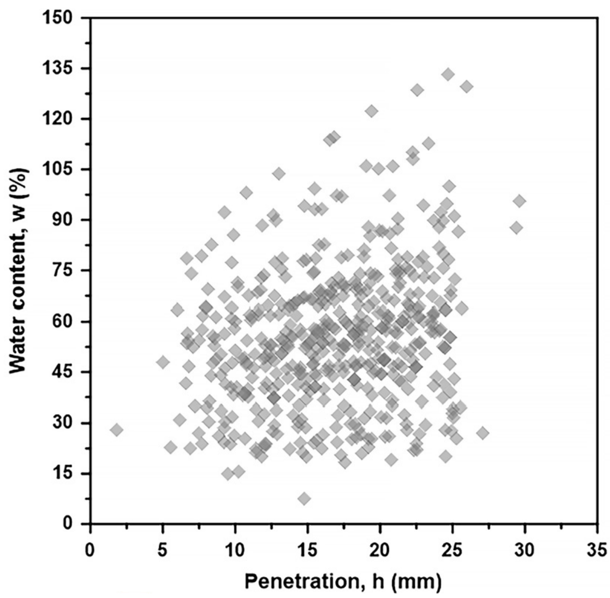


Fig. 2 The range of *h* and *w* for fall cone test

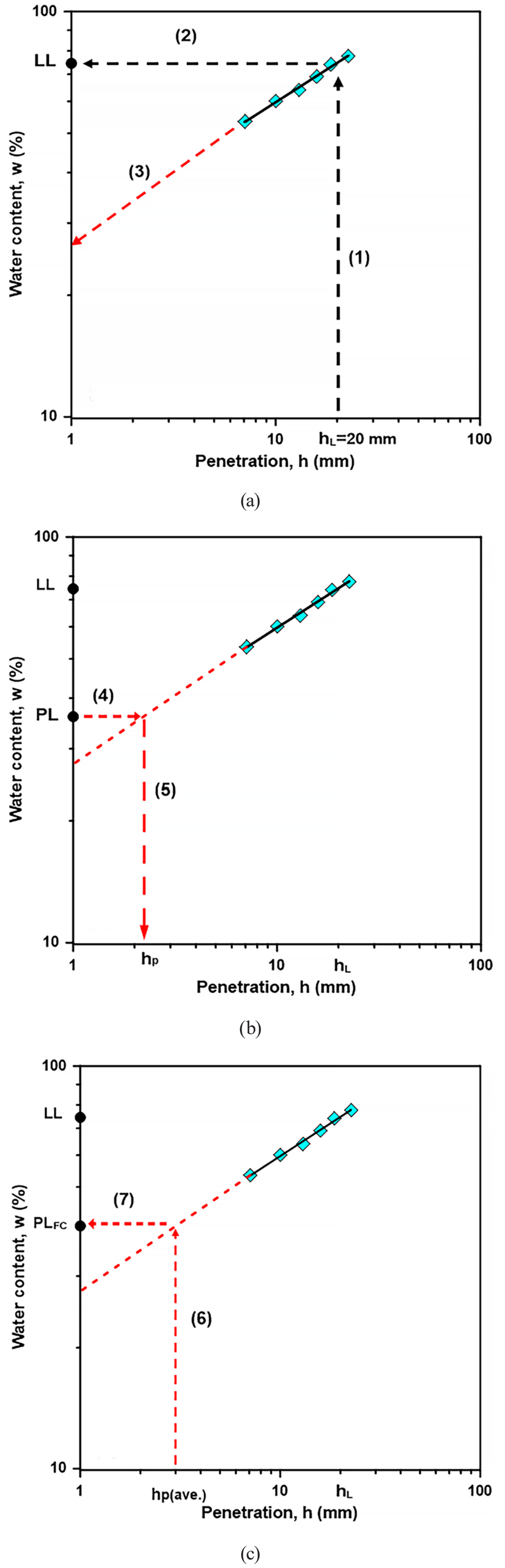


Fig. 3 Determination of PL_{FC} (a) determination of the LL_{FC} and extension of the slope line, (b) determination of the h_p corresponding to PL, (c) the PL_{FC} corresponding to the h_{pave}

- (4) on this double-sided logarithmic axis. The value of this intersection point on the x-axis is determined by following the process step,
- (5) and this penetration depth (h_p) on the x-axis is determined (Fig. 3 (b)). These steps were repeated for each soil, and 83 different h_p depths were determined. An average penetration depth (h_{pave}) was computed by taking the arithmetic average of the h_p values determined for each of the 83 soils. In the Fig. 3 (c), the water content value corresponding to the h_{pave} value determined by following steps,
- (6) and (7) was determined, and this value was called the modified plastic limit (PL_{FC}).

The steps displayed in Fig. 3 were repeated for each of the 83 soils, and the h_p and the PL distribution were plotted on the histogram in Fig. 4. When all data were analysed, the arithmetic mean of the h_p depths within the range of 1 mm and 5.6 mm equals 3 mm.

2.1 Determination of compaction parameters

Among 83 cohesive soils, 23 natural soils with LL_{FC} values ranging from 22.5% to 121.4% were used in the compaction tests. After that, standard compaction tests were performed on a total of 46 soils (3 SC-SM soils, 8 SC soils, 6 CL soils, 10 CI soils, 5 CH soils, 2 CV soils, 6 MH soils, and 6 MV soils) by adding different proportions of sand and gravel to these 23 soils. The soil properties presented in Table 2 were determined by preliminary laboratory

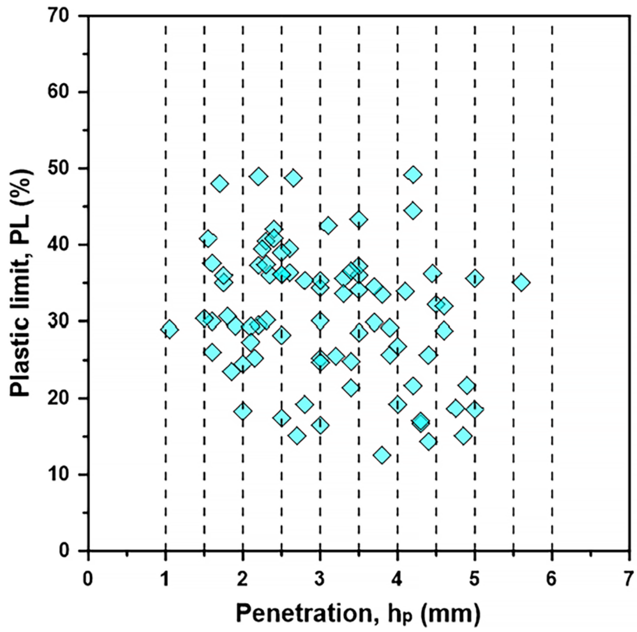


Fig. 4 Distribution of the penetration depths corresponding to the PL

Table 2 Soil properties and compaction parameters

Soil ID	Consistency limits			Grain size distribution				Compaction parameters		Soil type (BSCS)
	LL_{CUP} (%)	PL (%)	LL_{FC} (%)	G[1] (%)	S[2] (%)	M[3] (%)	C[4] (%)	OWC (%)	MDW (kN/m^3)	
S1	16.4	11.5	17.9	-	80.0	10.0	10.0	10.7	19.4	SC-SM
S2	17.8	12.6	21.3	-	79.5	13.0	7.5	10.6	19.7	SC-SM
S3	20.5	14.3	23.2	-	60.0	20.0	20.0	12.1	18.6	SC-SM
S4	22.5	15.1	25.8	-	69.3	19.5	11.3	12.7	19.1	SC
S5	22.7	18.5	25.7	-	28.0	52.0	20.0	15.3	18.3	CL
S6	23.0	15.2	27.6	-	82.8	5.6	11.6	11.7	18.9	SC
S7	23.4	13.3	26.0	25.0	24.0	25.0	26.0	13.2	18.7	CL
S8	23.4	13.3	26.0	25.0	50.0	12.5	12.5	8.6	21.4	SC
S9	28.1	16.5	31.2	-	40.0	30.0	30.0	14.4	17.9	CL
S10	28.5	19.2	31.8	-	38.0	41.0	21.0	21.3	15.4	CL
S11	31.0	18.7	34.5	-	59.0	26.0	15.0	15.5	17.8	SC
S12	31.5	17.4	34.2	-	8.0	62.0	30.0	15.7	18.0	CL
S13	31.6	18.8	35.8	-	25.0	37.5	37.5	19.0	16.8	CL
S14	34.0	18.3	38.8	-	65.6	11.2	23.2	14.1	18.5	SC
S15	36.1	21.4	39.0	-	20.0	40.0	40.0	18.3	16.9	CI
S16	37.2	23.6	41.2	-	48.8	32.5	18.8	20.0	16.6	CI
S17	38.5	29.4	41.5	-	22.0	65.0	13.0	20.2	16.0	CI
S18	40.8	26.0	45.0	-	22.0	71.0	7.0	22.2	16.7	CI
S19	41.0	25.0	44.2	-	-	48.0	52.0	22.5	15.8	CI
S20	41.2	25.7	44.2	-	-	50.0	50.0	22.7	15.8	CI
S21	42.2	26.8	47.2	-	38.5	39.0	22.5	23.7	15.7	CI
S22	42.5	19.1	44.3	25.0	31.0	21.5	22.5	16.3	17.8	SC
S23	42.5	19.1	44.3	25.0	53.0	10.8	11.3	10.1	20.3	SC
S24	46.0	23.5	49.5	-	48.4	16.8	34.8	18.2	17.5	CI
S25	46.5	28.2	49.2	-	16.0	49.0	35.0	22.5	16.7	CI
S26	49.8	27.3	52.0	-	-	57.0	43.0	27.5	14.4	CI
S27	51.0	36.0	55.0	-	19.0	42.0	39.0	25.8	14.9	MH
S28	52.5	31.9	54.5	-	28.3	45.5	26.3	27.5	14.8	CH
S29	54.5	34.1	57.0	28.0	16.0	18.0	38.0	29.0	15.3	MH
S30	55.0	35.7	58.5	-	18.0	52.0	30.0	31.5	13.5	MH
S31	56.6	21.2	58.4	-	17.0	45.0	38.0	22.9	15.9	CH
S32	57.4	27.2	60.8	-	34.0	32.3	33.8	21.3	16.5	CH
S33	57.5	35.3	60.2	-	-	67.0	33.0	25.1	15.8	MH
S34	60.5	30.7	63.0	-	8.0	32.0	60.0	23.4	15.5	CH
S35	60.5	47.7	60.0	-	5.0	76.0	19.0	33.5	14.4	MH
S36	60.7	47.7	60.0	-	5.0	76.0	19.0	33.5	14.4	MH
S37	66.4	28.4	68.5	-	31.2	22.4	46.4	23.7	15.9	CH
S38	70.7	26.4	71.6	25.0	23.0	15.0	35.0	26.5	15.5	CV
S39	70.7	19.9	71.6	25.0	50.0	7.5	17.5	16.7	17.3	SC
S40	71.0	35.0	73.0	-	14.0	28.0	58.0	29.1	14.4	MV
S41	74.5	36.1	75.0	-	12.0	43.0	45.0	29.1	14.3	MV
S42	84.9	48.7	86.0	-	-	46.0	54.0	35.1	13.3	MV
S43	95.5	37.5	98.3	-	25.0	22.5	52.5	36.5	12.8	CV
S44	97.0	63.5	97.0	-	10.0	24.0	66.0	48.0	11.8	MV
S45	97.5	48.0	98.2	-	-	20.0	80.0	37.5	11.5	MV
S46	124.0	49.9	121.4	-	-	30.0	70.0	44.3	11.8	MV

Note: [1]G:Gravel, [2]S:Sand, [3]M: Silt, [4]C:Clay tests carried out as part of this study. Before the standard compaction tests, the plastic and liquid limits of the soils containing different proportions of fine sand were determined. The PL is defined as the minimum water content at which soils can deform plastically. Therefore, the optimum water content required for maximum density in cohesive soils is expected to be equal to or less than the PL. For an ideal compaction curve, water contents above the PL also need to be considered. All compaction tests were performed at 6 different water contents. These water contents were defined as 40%, 55%, 70%, 85%, 95%, and 110% of the PL.

Before the compaction test, samples were stored in the humidity cabinet for 24 h. This methodology aims to attain a more homogeneous distribution of water content. After these procedures, compaction curves were generated for each soil sample, and compaction parameters (OWC and MDW) were derived from these curves. It has been observed that the optimum water content is generally in the range of 0.7 times PL to 0.95 times PL.

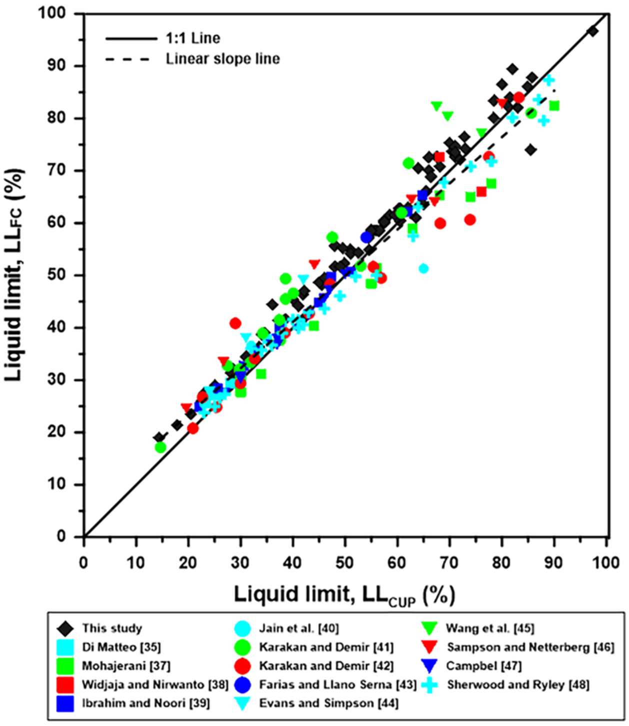
3 Results and discussion

The results of the experimental studies are presented in comparison with a comprehensive database from the literature. Particular attention was paid to ensuring that the consistency limits and grain size distribution of the soils in the database were similar to the soil properties used in this study.

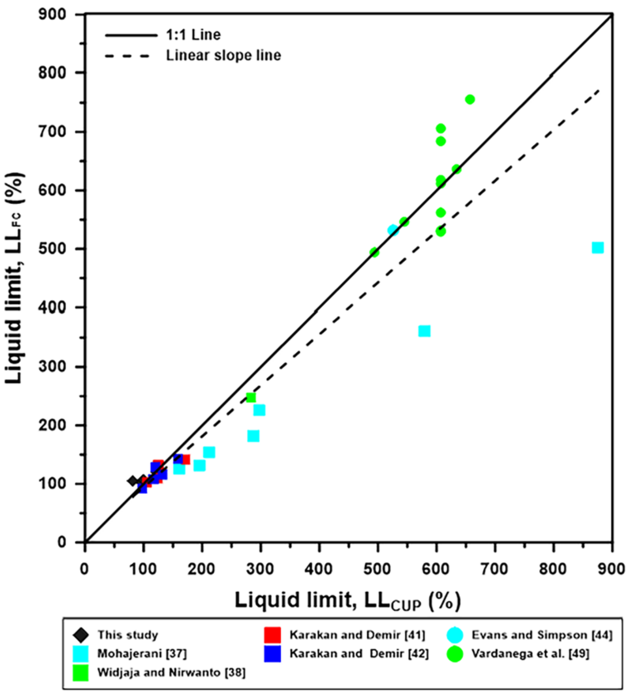
3.1 Consistency limits

In Fig. 5, the LL_{CUP} and LL_{FC} are presented together with the studies in the literature [35, 37–39, 40–49].

The primary distinction between the traditional Casagrande method and the fall cone test pertains to the precision and reliability of the measured liquid limits. The Casagrande method is predicated on groove closure under repeated impacts, making it operator-dependent and susceptible to variability. Conversely, the fall cone test offers a more objective and replicable measurement by quantifying the penetration depth under a standardised cone weight. In this study, the liquid limit of each soil sample was measured twice. For samples with a LL(%) below 100%, the Casagrande method exhibited a variation of approximately 2%, while the fall cone test demonstrated a variation of around 0.5%.This finding indicates the fall cone test's higher precision and reliability. Fig. 5 (a) shows that for soils with LL less than 100%, the two LL values are close to each other, and in most cases, the LL_{CUP} is either equal to or less than the LL_{FC}. A total of 193 soils were evaluated, employing 78 soils for this study (Fig. 5 (a)). More specifically, Di Matteo [35], Mohajerani [37], Widjaja and Nirwanto [38], Ibrahim and Noori [39], Jain et al. [40], Karakan and Demir [41, 42],



(a)



(b)

Fig. 5 Comparison of the LL_{CUP} and LL_{FC} obtained (a) $LL_{FC} < 100\%$, (b) $LL_{FC} \geq 100\%$

Farias and Llano Serna [43], Evans and Simpson [44], Wang et al. [45], Sampson and Netterberg [46], Campbell [47], Sherwood and Ryley [48] have a total of 9, 2, 5, 16, 15, 1, 3, 3, 6, 11, 6, 13, 25 soils, respectively. Additionally, the number of samples with LL_{FC} less than 100% is not only considerably high, but the liquid limits also vary within a wide range. However, for soils with LL_{FC} equal to or greater than 100%, the LL_{CUP} is prone to be greater than the LL_{FC}, and the difference between them rises with the increase in the liquid limits, as shown in Fig. 5 (b), but the number of samples is very limited. In particular, 5 out of 39 soils belong to this study, as shown in Fig. 5 (b). For those where the LL_{FC} is more significant than 100%, Mohajerani [37], Vardanega et al. [49], Widjaja and Nirwanto [38], Karakan and Demir [41, 42], Evans and Simpson [44] have 1, 16, 4, 5, 1 and 7 soils respectively. In addition, in Fig. 5, R_1^2 values represent the correlation coefficient calculated by including the soils in this study, while the R_2^2 values represent the correlation coefficient calculated using only the literature data. The relevant figures display the two distinct correlation coefficients that were computed.

Within the scope of this study, PL_{FC} values were determined for 83 soils following the steps detailed in Fig. 3. Fig. 6 illustrates the relationship between PL_{FC} and PL.

It was found that there is a consistent trend between the PL and PL_{FC} values obtained from the different methods. The agreement between the regression line and the 1:1 line is high for PI values between 13% and 36%, but the regression line moves away from the 1:1 line as higher PL values are considered.

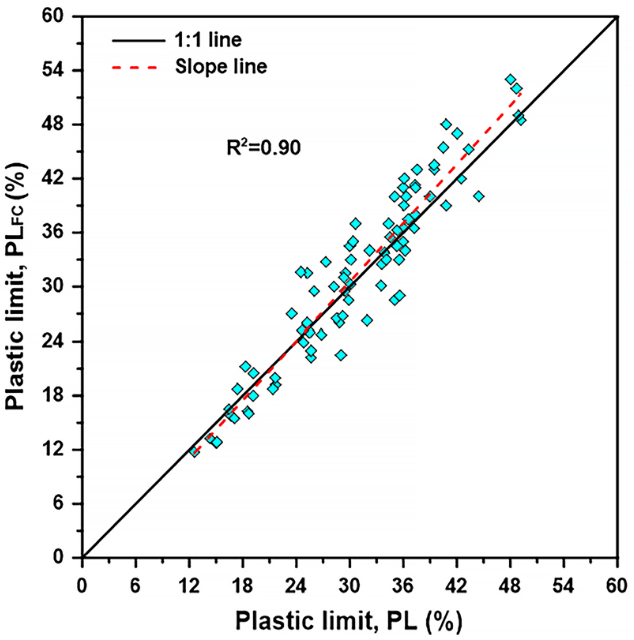


Fig. 6 The variation between the PL and PL_{FC} for a total of 83 cohesive soils

A comparison of liquid limits was obtained from different test methods for this study and the literature. The h_p depth corresponding to the PL obtained from the h vs. w relationship of the fall cone test was applied to the studies in the literature using the fall cone at 30° and 80 g. For this purpose, the data for the studies reviewed and the 203 soils used in this study (24 clay and sand mixtures, 2 clay and additive mixtures, 7 clay and clay mixtures, and 170 natural cohesive soils) are presented in Table 3. When reviewing the literature, attention has been paid to ensuring that the LL values of the soils used are close to the LL_{FC} of the soils used in this study, and studies involving soils with an LL_{FC} greater than 121.4% were not used [35, 39, 42, 44–48, 50–54].

The h_p corresponding to the PL in the fall cone h and w relationship for the data from different researchers in Table 3 was investigated by the following procedure in Fig. 3, and it was found that the obtained h_p depths may be different for each study. Noticeably, the h_p values are exceptionally high in soils containing clay-sand and clay- additive mixtures. In this study, the PL_{FC} was determined for each study in Table 3, using the proposed value of h_{pave} equal to 3 mm, and it was observed that the PL and PL_{FC} obtained by two different methods agreed, although there were some outliers, as shown in Fig. 7 [35, 39, 42, 44, 46–48, 50–54].

According to the Unified Soil Classification System (USCS), approximately 594 samples, having 46 soils for this study in the database, were classified as 216 CL, 20 ML, 1 OL, 124 CH, 76 MH, 79 SC, 9 SM, 1 SP, 54 GC, 5 GM, 5 GW, and 4 GP in Table 4 [3, 4, 6, 8–10, 28–30, 32, 33, 36, 55–57]. The liquid limits of these soils range from 16.4% to 121.4%, and the plastic limits are within the range of 8.0% and 63.5%. Furthermore, the OWC values are between 6% and 48%, and MDW values are in the range of 9.6 kN/m³ and 21.4 kN/m³.

Fig. 8 [3, 4, 6, 8–10, 28–30, 32, 33, 36, 55–58] shows a strong trend between the OWC and MDW in a wide range, except for some outliers. A limited number of data, which distorts the general pattern, drastically affects R^2. Although the R^2 for the relationship between the OWC and MDW is 0.83 when considering all data, it increases to 0.89 when only four sample data were excluded. In addition, the R^2 determined using 590 soils, excluding these four outlier data points in the database, was computed as 0.89, while the R^2 calculated for 544 soils without including the 46 soils used in this study was 0.87. As a result, it was observed that the data used in this study contributed positively to the database and increased the R^2.

Table 3 The fall cone test results compiled from the literature

Source	Total count	Count LL$_{FC}$ <100 (%)	Count LL$_{FC}$ ≥100 (%)	Ave. test points	Thread rolling: PL (%) Max.	Min.	Ave.	Fall cone test: w (%) Max.	Min.	Ave.	Penetration (mm) Max.	Min.	Ave.	h_p (mm) Max.	Min.	Ave.
This study	83	78	5	6	63.5	12.6	31.3	135.0	7.6	54.3	29.6	1.96	16.9	5.6	1.1	3.0
Di Matteo [35]	6	6	0	12	24.0	18.0	20.2	42.7	25.5	33.5	26.2	14.9	19.8	4.1	1.8	3.1
Feng [50]	5	5	0	12	25.0	19.0	22.7	397.7	21.7	89.1	25.5	3.2	12.3	3.4	2.3	2.8
Harison [51]	7	7	0	6	45.0	38.0	40.1	110.8	47.2	70.4	26.4	5.4	16.1	3.1	2.0	2.5
Sivakumar et al. [52]*	16	13	1	4	35.4	16.2	26.7	95.9	30.1	61.5	24.6	15.0	19.4	5.5	1.0	2.3
Ibrahim and Noori [39]	9	9	0	4	34.4	15.8	24.7	66.8	19.3	44.0	26.9	13.7	20.0	12.0	3.0	5.8
Karakan and Demir [42]	20	16	4	5	54.0	18.3	30.8	141.1	14.1	52.4	40.6	3.1	19.5	13.0	1.9	6.3
Evans and Simpson [44]	4	3	1	4	29.0	16.0	24.0	55.2	22.4	37.2	29.8	8.7	19.5	7.3	3.0	4.7
Wang et al. [45]	3	3	0	7	46.3	35.3	42.1	90.0	51.3	68.9	28.4	7.0	14.6	4.5	3.6	4.1
Sampson and Netterberg [46]	6	6	0	8	37.9	18.2	28.2	88.6	19.2	46.1	24.6	0.3	12.5	3.0	1.0	1.8
Campbell [47]	13	13	0	4	44.0	22.0	29.9	51.9	25.8	37.8	26.7	3.5	17.8	12.0	1.3	5.7
Sherwood and Ryley [48]	25	25	0	4	43.0	12.0	23.7	89.0	20.5	48.9	28.7	11.9	19.9	8.0	1.0	2.6
Llano Serna and Contreras [53]	3	3	0	38	36.0	14.0	23.3	91.5	23.6	56.2	39.4	3.7	20.1	3.4	1.0	2.1
Zentar et al. [54]	5	5	0	6	43.6	23.6	37.9	111.4	23.5	68.3	32.0	3.7	19.0	6.8	3.7	5.0

*Although the total number of soils is 16, two are excluded from the evaluation due to non-plastic.

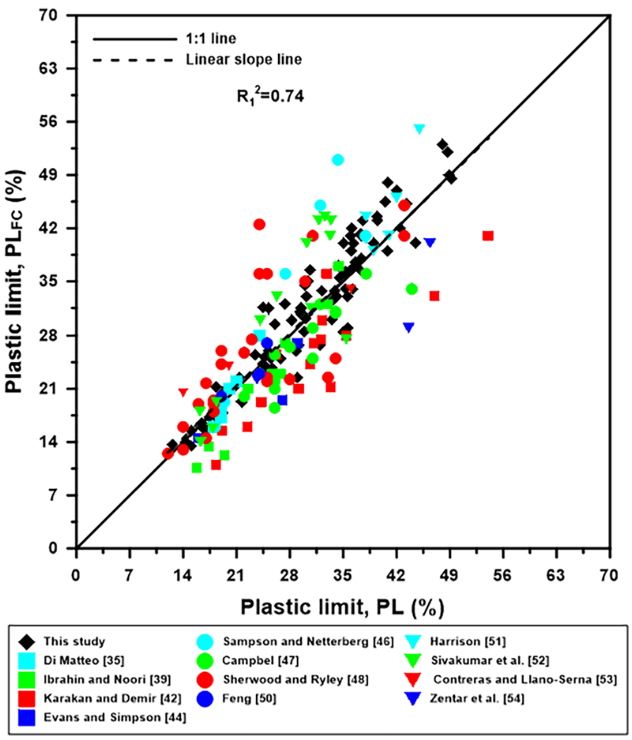


Fig. 7 Comparison of the PL and PL$_{FC}$ for this study and literature

In Table 3, the soil properties considered in each study differ. Wang et al. [45] focused on three cohesive soils with high plasticity, resulting in higher PL and w values. In contrast, Di Matteo [35] examined six soils with low plasticity, leading to lower PL and w values. Therefore, this study includes soil properties from both low-plasticity and high-plasticity soils, thus facilitating more comprehensive evaluations. Notably, the minimum water content and penetration values in this study are lower than those in other studies. This was done to bring the data in Fig. 3 as close to the Y-axis as possible. The wide range of data selected from the literature allowed for a more comprehensive comparison. Furthermore, the water retention potential and compressibility of soils are influenced by their mineralogical composition, which is closely related to their consistency limits. The significant differences in data values observed in Table 3 are primarily attributed to variations in soil type and consistency limits.

An analysis of the soil properties presented in Table 4 reveals that the majority of researchers investigating the relationship between consistency limits and compaction

Table 4 Consistency limits and compaction parameters compiled from literature studies

Source	Total count	LL_{CUP} (%)			PL (%)			OWC (%)			MDW (kN/m³)		
		Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.
This Study	46	124.0	16.4	48.9	63.5	11.5	26.7	48.0	8.6	22.2	21.4	11.5	16.4
Nagaraj et al. [3]	42	115.0	24.0	48.5	45.3	17.4	27.9	36.8	9.5	21.5	18.3	12.6	15.7
Blotz et al. [4]	14	62.0	17.0	36.6	24.0	8.0	16.2	25.0	8.9	16.1	20.5	14.9	18.2
Sridharan and Nagaraj [6]	10	73.5	37.0	54.7	51.9	18.0	33.8	44.4	16.2	30.0	17.9	11.1	14.0
Jyothirmayi et al. [8]	9	72.0	41.2	54.7	32.5	20.7	25.7	21.5	16.7	19.2	18.7	12.7	15.9
Ng et al. [9]	9	53.0	41.0	45.6	34.0	26.0	29.0	24.0	13.5	17.9	17.1	14.4	15.9
Saikia et al. [10]	40	56.2	20.8	35.9	29.9	10.0	20.3	31.0	15.1	22.1	18.6	13.8	16.4
Hussain and Atalar [28]	8	76.8	43.2	56.9	25.7	18.0	21.3	22.5	15.5	18.8	19.6	15.6	17.0
Fondjo et al. [29]	15	59.7	40.3	59.7	21.7	17.8	21.7	22.1	17.2	22.1	17.7	15.7	17.7
Al Khafaji [30]	88	66.0	14.0	40.1	29.0	10.0	20.2	26.0	9.0	19.2	18.8	10.5	16.7
Tsegaye et al. [32]	56	97.0	55.4	66.6	41.0	22.0	28.4	37.0	15.5	24.1	17.3	12.3	15.0
Firomsa and Quezon [33]	30	103.0	76.0	88.6	59.0	33.0	47.6	40.0	32.0	35.4	13.8	11.9	12.9
Günaydin [36]	126	56.7	23.1	39.7	29.8	13.7	21.6	26.0	7.6	16.3	20.5	14.0	17.5
Benson and Trast [55]	10	70.0	24.0	43.1	32.0	12.0	17.8	24.0	10.0	16.1	20.4	15.4	17.9
Daniel and Benson [56]	2	55.0	34.0	44.5	28.0	16.0	22.0	29.4	17.5	23.5	17.3	14.4	15.8
Ören [57]	9	92.4	33.4	56.5	42.3	17.5	27.7	36.3	20.0	25.1	16.2	11.8	14.6

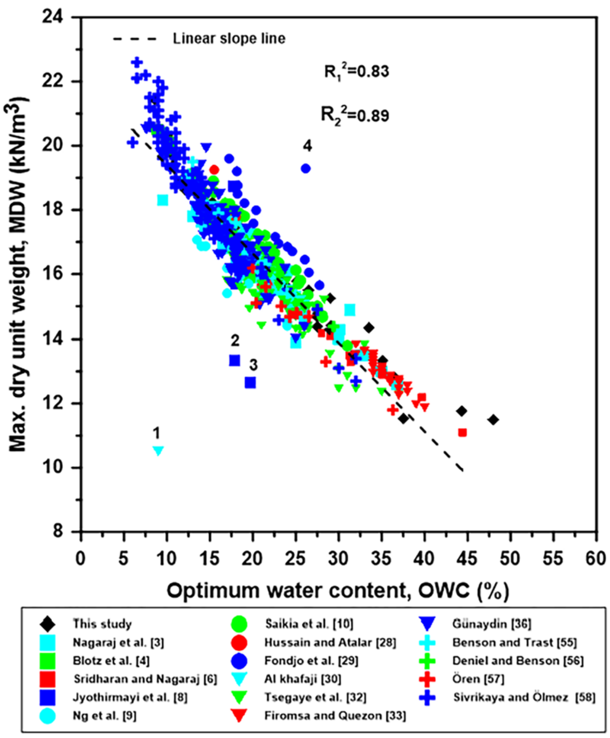


Fig. 8 The relationship between compaction parameters for this study and the literature

parameters consider both low-plasticity and high-plasticity soils to ensure a comprehensive assessment. In a similar manner, the present investigation follows the same principle in selecting soil properties.

When the studies analysed to constitute the database were evaluated, several approaches were used to estimate compaction parameters from consistency limits. Fig. 9 [10, 28, 29, 33] presents the studies indicating that MDW and OWC values show a correlative relationship with liquid limits. While the R^2 values calculated for these studies show a strong degree of agreement, the equations proposed in Table 5 [10, 27–29, 33] differ slightly.

Several researchers have reported that MDW and OWC values show better correlations with PL than LL, as shown in Fig. 10 [3, 6, 8, 32, 58]. The studies that consider the PL value for the estimation of compression parameters demonstrate a high degree of consistency in their data, both within themselves and in comparison to other studies. Additionally, the equations proposed in Table 6 [3, 6, 8, 58, 59] exhibit notable similarities.

Several researchers highlighted the importance of evaluating the PL and LL together to estimate the MDW and OWC [30–33]. Therefore, the researchers obtained higher R^2 through this approach. While the results presented in Table 7 [10, 30–33] for each study align with the perspectives of the researchers, the R^2 values in Table 5 and Table 6 may be higher.

The equations obtained from database-based regression analysis vary according to the grain size distribution and liquid and plastic limit values of the soils used in each study. In addition, this situation has been extensively

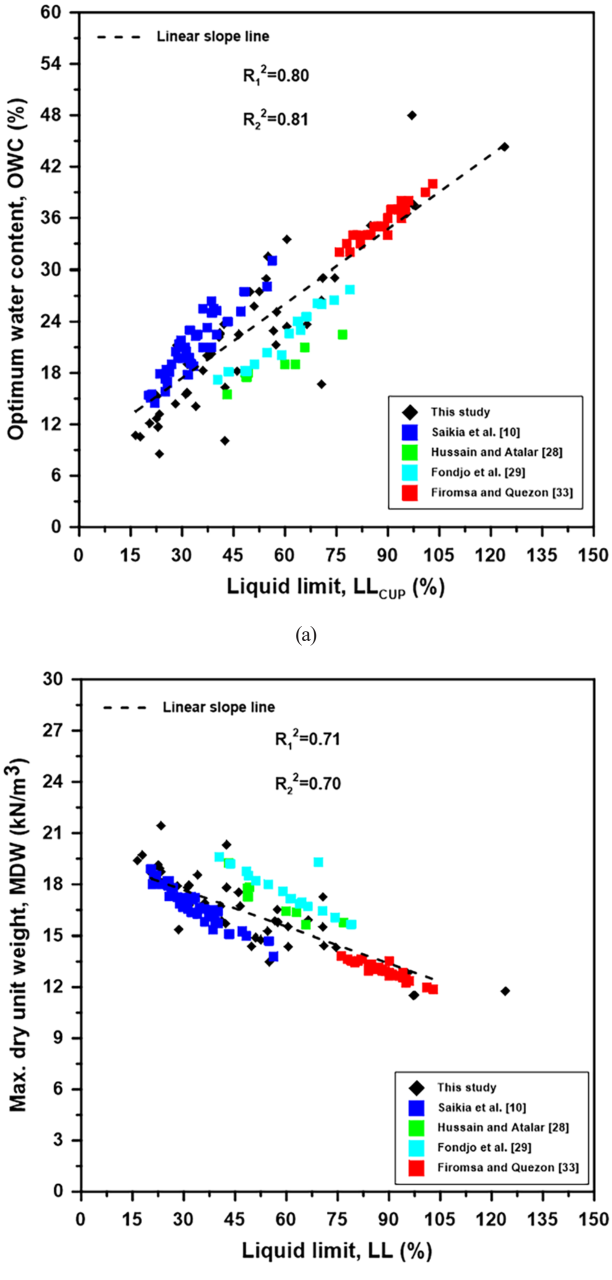


Fig. 9 The relationship between compaction parameters and liquid limit (a) OWC and LL_{CUP}, (b) MDW and LL_{CUP}

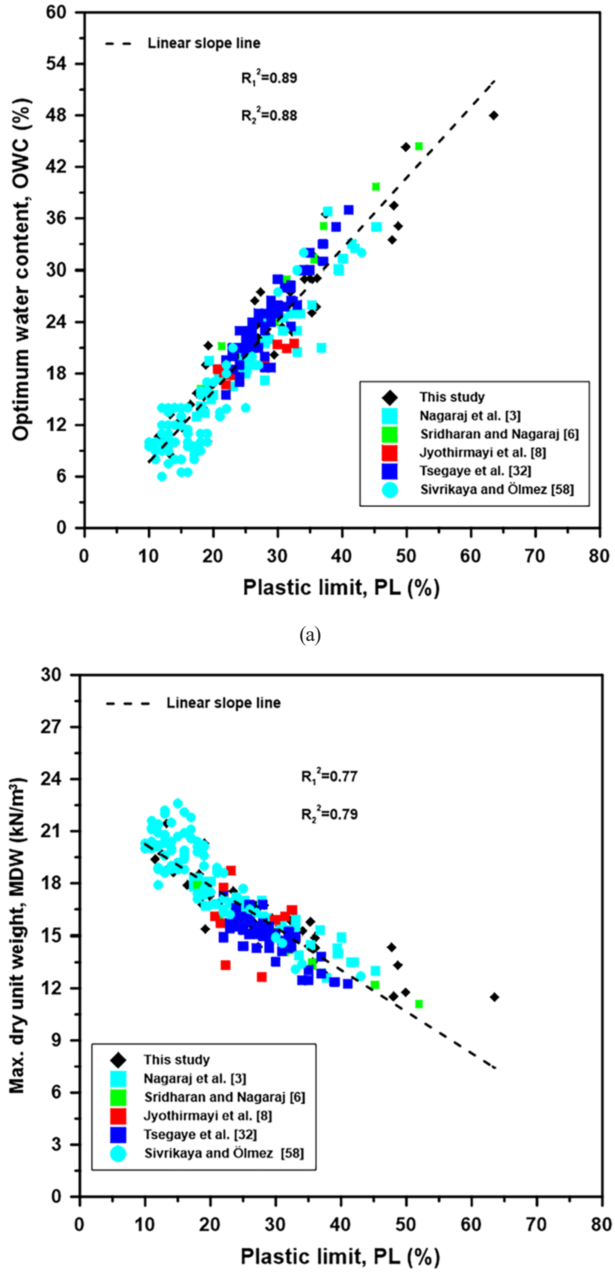


Fig. 10 The relationship between compaction parameters and PL (a) OWC vs. PL, (b) MDW vs. PL

Table 5 Correlations for estimation of compaction

Source	Count	OWC (%) vs. LL (%)	R^2	MDW (kN/m³) vs. LL (%)	R^2
This study	46	$OWC = 0.33\ LL_{CUP} + 5.95$ $OWC = 0.35\ LL_{FC} + 4.42$	0.79 0.79	$MDW = 20.26 - 0.08\ LL_{CUP}$ $MDW = 20.65 - 0.08\ LL_{FC}$	0.71 0.72
Saikia et al. [10]	40	$OWC = 0.42\ LL_{CUP} + 7.22$	0.85	$MDW = 20.95 - 0.13\ LL_{CUP}$	0.90
Gurtug et al. [27]	106	$OWC = 0.30\ LL_{CUP} + 4.00$	0.89	$MDW = 41.97\ LL^{-0.127}$	-
Hussain and Atalar [28]	8	$OWC = 0.18\ LL_{CUP} + 8.52$	0.91	$MDW = 22.57 - 0.10\ LL_{CUP}$	0.82
Fondjo et al. [29]	15	$OWC = 9.57\ e^{0.0138\ LL_{CUP}}$	0.96	$MDW = 24.78\ e^{-0.006\ LL_{CUP}}$	0.98
Firomsa and Quezon [33]	30	$OWC = 0.28\ LL_{CUP} + 10.43$	0.90	$MDW = 19.16 - 0.07\ LL_{CUP}$	0.87

Table 6 Correlations for estimation of compaction parameters using PL

Source	Count	OWC (%) vs. PL (%)	R^2	MDW (kN/m^3) vs. PL (%)	R^2
This study	46	OWC = 0.75 PL + 2.10 OWC = 0.63 PL_{FC} + 4.70	0.91 0.87	MDW = 21.14 – 0.18 PL MDW = 20.49 – 0.15 PL_{FC}	0.81 0.76
Nagaraj et al. [3]	42	OWC = 0.76 PL + 0.14	0.86	MDW = 21.06 – 0.18 PL	0.87
Sridharan and Nagaraj [6]	10	OWC = 0.83 PL + 2.04	0.97	MDW = 20.41 – 0.19 PL	0.94
Jyothirmayi et al. [8]	9	OWC = 12.00 $e^{0.018\,PL}$	0.84	-	-
Shimobe et al. [59]	33 33	OWC = 0.77 PL + 3.00 OWC = 0.55 PL + 7.27	0.78 0.93	MDW = 19.39 – 0.02 PL MDW = 17.34 – 0.01 PL	0.80 0.79
Sivrikaya and Ölmez [58]	75	OWC = 0.77 PL + 0.36	0.73	MDW = 23.90 – 0.28 PL	0.66

Table 7 Correlations for estimation of compaction parameters using PL and LL

Source	Count	OWC (%) vs. LL (%) and PL (%)	R^2	MDW (kN/m^3) vs. LL (%) and PL (%)	R^2
This study	46	OWC = 0.58 PL + 0.09 LL_{CUP} + 2.09 OWC = 0.49 PL_{FC}+ 0.10 LL_{FC} + 3.78	0.93 0.89	MDW = 21.15 – 0.13 PL – 0.02 LL_{CUP} MDW = 20.78 – 0.10 PL_{FC} – 0.03 LL_{FC}	0.83 0.78
Saikia et al. [10]	40	OWC = 0.16 PL + 0.35 LL + 6.26	0.86	MDW = 21.07 – 0.02 PL – 0.12 LL	0.90
Al Khafaji [30]	88	OWC = 0.63 PL + 0.24 LL – 3.13	-	MDW = 23.90 – 0.20 PL – 0.08 LL	-
Đoković et al. [31]	72	OWC = 0.32 PL + 0.16 LL + 4.18	0.86	MDW = 21.00 – 0.05 PL – 0.07 LL	0.86
Tsegaye et al. [32]	56	OWC = 0.62 PL + 0.08 LL + 1.49	0.88	MDW = 21.83–0.15 PL – 0.04 LL	0.83
Firomsa and Quezon [33]	30	OWC = 0.23 PL + 0.11 LL + 9.74	0.89	MDW = 17.54–0.03 PL – 0.04 LL	0.75

analysed in the literature through the application of various machine learning techniques to predict soil properties and compaction behaviour. In particular, artificial neural networks (ANNs) have been employed for their capacity to model complex, non-linear relationships between soil characteristics and compaction outcomes. Furthermore, the integration of artificial intelligence (AI)-supported software has enabled the processing and analysis of extensive datasets, facilitating the development of highly accurate predictive models.

4 Conclusions

Consistency limits and compaction parameters are important engineering properties for designing various geotechnical applications, particularly where soils are used as construction materials and backfill. It is, therefore, necessary to check these parameters using alternative test methods and correlations available in the literature. This study proposed a modified plastic limit method by considering the relationship between water content and penetration depth derived from fall cone tests for soils with wide grain size distributions and index properties. Compaction parameters with high correlations were estimated using LL_{FC} and PL_{FC} values determined from a single test device. The results are summarised below.

1. Comparing the liquid limits determined from the Casagrande and fall cone tests, the LL_{CUP} is lower than the LL_{FC} for cohesive soils when the LL_{CUP} is less than 100%. In particular, there is a strong relationship between these two values, with R^2 up to 0.95. In contrast, the LL_{CUP} is greater than the LL_{FC} for soils when the LL_{CUP} is either equal to or higher than 100%, and this margin rises with an increment in the liquid limit. Therefore, the relationship between the LL values weakens and R^2 decreases to 0.83. This finding is generally valid for the soil used in this study and for a large data set compiled from literature studies.
2. A new approach has been proposed to determine the plastic limit from the fall cone test. The method was tested on this study's soils and a large data set collected from the literature. The findings showed that the water content corresponding to a 3 mm penetration can be used for the PL_{FC}. Despite some outliers, a satisfactory coefficient of determination (R^2 = 0.76) was achieved between PL and PL_{FC}.
3. A large data set compiled from the literature has shown that the h_p depths corresponding to PL varied from 1 mm to 5.6 mm. While soils with particularly high h_p values are typically clay- sand and clay-additive soils, more consistent results have been obtained for naturally cohesive soils.
4. In the univariate regression analyses performed for 594 compaction parameters and consistency limits in

the database, the most compatible results for predicting OWC and MDW values were obtained using plastic limit values. In addition, the R^2 values calculated from univariate analyses for this study were 0.81 and 0.91 for PL, and 0.76–0.87 for PL_{FC}. These values are consistent with the results reported in the literature.

5. Although the R^2 = 0.93–0.83 calculated by evaluating the plastic and liquid limits together in multivariate regression analyses for estimating OWC and MDW represents the optimised case for this study, it is quite close to that of the univariate regression analysis considering PL and PL_{FC}.
6. Considering the multivariate regression analyses between the consistency limits of the different test methods and the compaction parameters, it was found that the compaction parameters could be calculated with a high R^2 based on the PL_{FC} and LL_{FC} obtained from a single test device, in addition to the equations suggested in the literature.

Recommendations

The results of this study were based on experimental data and supported by regression analysis. A comprehensive dataset is available in the literature, which can be used to develop a database for further analysis. Machine learning or AI-based methods could enhance these analyses, reducing the experimental workload and enabling a more comprehensive evaluation of soils with different properties.

Acknowledgement

The authors extend their gratitude to Hasan Adiyaman, Asst. Prof. Dr. Serhan Ulukaya, and the staff of the Yildiz Technical University Geotechnical Laboratory for their valuable contributions to this study.

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