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Comparing the Casagrande and the Fall Cone Penetrometer Devices using Lateritic Soils Developed on Different Parent Rocks

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Abstract

A comparison between the Casagrande cup method and the Fall cone penetrometer devices for determining the liquid limit (LL) was conducted on lateritic soils developed on basalt, granite, and gneiss in the northeast area of Dschang city. The goal was to identify which device provides more reliable results. A total of 133 soil samples were collected and tested using both methods. Additionally, nine representative samples from each parent rock type underwent geotechnical analysis. The granulometric analysis combined with the Atterberg limits enabled soil classification for each substrate. Soils on basalt and gneiss are classified as high plasticity clays, while those on granite are low plasticity clays. Data were analyzed using Microsoft Excel and SPSS version 26. The findings indicated that the Fall cone device produced more accurate results than the Casagrande apparatus, although the difference was not statistically significant. A correlation analysis showed a strong positive relationship between the two methods for soils on basalt, expressed as: LLc = 0.78 LLp + 16.50, with an R^2 of 0.60. The correlation was moderate ($R^2 = 0.4$) for soils on granite and weak ($R^2 = 0.1$) for soils on gneiss. This relationship should not be generalized to specific soil types, as it is affected by soil plasticity and device configuration.

Keywords

Dschang, Lateritic Soil, Casagrande Apparatus, Liquid Limit, Fall Cone, Soil Classification

1. Introduction

Atterberg limits, including the liquid limit (LL) and plastic limit (PL), are common tests used in Geotechnical Engineering and Agriculture. These limits originated from studies conducted by Swedish agronomist Atterberg (1911) and were later standardized by Terzaghi (1926). They are used in Civil Engineering for classifying fine-grained soils. There are three Atterberg limits: the liquid limit (the water content at which soil shifts from liquid to plastic with minimal shear strength), the plastic limit (the water content at which soil transitions from plastic to solid), and the shrinkage limit. The liquid limit (LL) is a key parameter in Geotechnical Engineering, vital for classifying and evaluating other soil properties. It helps determine clay activity, plasticity index, compression, and recompression index, and provides insights into soil bearing capacity and settlement (Jain et al., 2021). The measurement of soil liquid limit was refined by Casagrande (1932), who standardized the procedure to ensure reproducible results, leading to the development of the liquid limit testing apparatus and methods currently outlined in (ASTM D4318-10, 2015) and (AASHTO, 1995). Although the Atterberg limits are primary parameters for soil identification and classification, their accuracy can be biased, as the liquid limit depends on the method of determination, not solely the soil's intrinsic properties. Consequently, a soil might be classified incorrectly if the method is not precisely followed, which is why accurate LL determination is critical (Di Matteo et al., 2016). In 1958, Casagrande criticized the 1932 apparatus setup due to non-repeatable results caused by non-standard equipment and the inflexibility of the cup's base (Casagrande, 1958). Furthermore, Hansbo (1957) found the Casagrande method tedious and manual, reducing efficiency and repeatability. He introduced the Fall cone penetrometer, which is believed to yield more reliable LL results than Casagrande's apparatus (Christaras, 2009; Özer, 2009; Spagnoli, 2012; El-Shinawi, 2017; Di Matteo et al., 2016; Crevelin & Bicalha, 2019; Ibrahim, Krikar, & Noori, 2019). Notably, the European standard CEN ISO/TS 17892-12 2004 has adopted the Fall cone penetrometer as the standard for LL determination, with the Casagrande method designated as an alternative.

The comparison between the Casagrande cup device and the Fall cone penetrometer has been the focus of numerous studies. These studies generally conclude that LL values obtained with the Fall cone penetrometer are about 3% higher than those from the Casagrande device (Budhu, 1985; Christaras, 2009; Özer, 2009; Spagnoli, 2012; El-Shinawi, 2017; Di Matteo et al., 2016; Crevelin & Bicalho, 2019; Ibrahim, Krikar & Noori, 2019). Due to its semi-automatic to automatic design, the Fall cone penetrometer seems to provide better LL results compared to the Casagrande device. Many researchers have compared both devices and found the Fall cone to be superior (Bicalho et al., 2014). The assumption that LLp values from the Fall cone are greater than LLc values from the Casagrande device is valid primarily for soils with low plasticity. In contrast, for high plasticity soils, the results are reversed, with LLc exceeding LLp (Budhu, 1985). For soils with medium plasticity, the comparison is less straightforward (Bicalho et al., 2014). According to the LCPC-SETRA classification, soil plasticity is based on the plasticity index

(PI): soils with a PI between 5 and 15 are considered low plasticity, those with a PI between 15 and 40 are medium plasticity, and soils with a PI over 40 are high plasticity. However, there is no strict criterion for the soil's liquid limit and plasticity index ranges, so researchers often define their boundaries between low and high plasticity soils. Mishra et al. (2012) noted that, in comparing the devices, LLc was higher than LLp for soils with LL values between 77 and 135, which Mishra considers to be very plastic soils with LL values greater than 77. Di Matteo (2012) suggested that soil LL values should be between 20 and 50 to support his hypothesis. Kollaros (2016) agrees with Mishra that for LLp > LLc, the LL should be between 0 and 70%. Ibrahim et al. (2019) observed that LL values between 15 and 66% support the idea that Fall cone LLp results are higher than Casagrande LLc results; similar findings were reported by Bicalho et al. (2014), where LL values ranged from 14% to 98%. Since the boundary between low and high plasticity soils is not fixed, Kollaros (2016) classifies low plasticity soils as those with LL between 0 and 70%, and high plasticity soils as those with LL above 70%. Shimobe & Spagnoli (2019) define low-plasticity soils as those with LL below 120%, in which case the Fall cone device produces higher LLp values than the Casagrande LLc. In high-plasticity soils (LL > 120), the LLp values from the Fall cone become lower than the LLc values from Casagrande.

The lack of standardization among various Casagrande devices makes it challenging to determine the liquid limit. The base on which the Casagrande cup rests can be either hard or soft. Typically, LLs measured with the hard-base Casagrande apparatus are higher than those obtained with the soft-base version (Crevelin & Bicalho, 2019). The hard-base Casagrande device generally reports a lower LL than the Fall cone penetrometer for soils with LL below 70%, while with the soft-base device, LLc exceeds LLp for soils with LL above 40% (Özer, 2009). However, the difference between the Russian and British Fall cone penetrometers is not significant (El-Shinawi, 2017). Although the configurations of different penetrometers are similar, standardization remains a debated issue because the penetration corresponding to the LL is not standardized worldwide. According to the French standard NF P 94-052-1, LL corresponds to 17 mm penetration, whereas the Moroccan standard NM 13.1.012 requires 20 mm penetration to determine LL. Some researchers argue that 20 mm may not be an appropriate standard for all soil types and suggest increasing it to 29 mm, especially for highly plastic soils. This has led to the development of the NCCLL penetrometer with new calibration lines for cone penetrometer liquid limit (30˚, 80 g, and 29 mm) (Hrubesova et al., 2016). Several studies comparing the Casagrande device and the Fall cone penetrometer show that the Fall cone typically yields liquid limits about 3% - 5% higher than the Casagrande method, and the relationship between the two depends on soil properties such as mineralogy and plasticity (Christaras, 2009; Özer, 2009; Spagnoli, 2012; Mishra et al., 2012; El-Shinawi, 2017; Di Matteo et al., 2016; Crevelin & Bicalho, 2019; Ibrahim, Krikar, & Noori, 2019). These studies have mainly been conducted worldwide, except in the subtropics, where abundant laterites are often used in infrastructure (Sikali & Mir-Emerati, 1987). This study aims to compare these two devices on lateritic soils from different origins to recommend the most suitable one. Additionally, it will contribute to the existing database of correlations between the Casagrande device and the Fall cone penetrometer, depending on LL range and geological formation. As Di Matteo (2012) notes, comparing results across studies is difficult due to varying geological characteristics of clay formations, which emphasizes the importance of comparing LL values of laterites formed on granite, basalt, and gneiss for both devices. Ultimately, this promotes the sustainable use of lateritic materials in infrastructure, as classification and application will no longer be speculative.

2. Materials and Methods

2.1. Location of Study Area

The study area is situated northeast of the town of Dschang in the Menoua Division of Cameroon's West Region. It is bounded by latitudes 5˚26'00" and 5˚28'00" north of the Equator and longitudes 10˚20'00" and 10˚50'00" east, as shown in Figure 1. The climate at high altitude is sub-equatorial, characterized by two seasons annually: a long rainy season spanning eight months from March to October, and a short dry season lasting four months. The yearly rainfall is 1782.3 mm, with an average monthly rainfall of 148.5 mm, and the mean annual temperature is 20.4˚C. The Menouet River and its tributaries drain the Dschang area, originating from the Bamboutos Mountains (Bouyo Houketchang, 2003). The

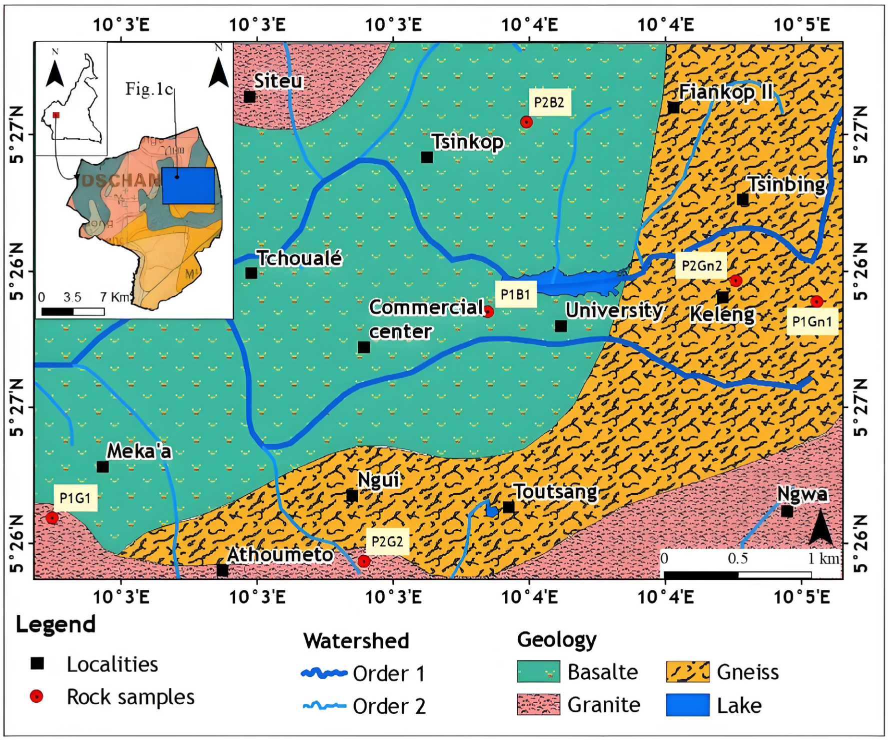

Figure 1. Location map of study site.

hydrographic network in this region is sparse, displaying a dendritic to subparallel pattern. Dschang is located at the foot of the Bamboutos Mountains, where two geological formations are exposed (see **Figure 1**): volcanic formations and basement formations. The volcanic formations include alkaline plateau basalts, ignimbrites, phonolites, and trachytes, while the basement formations consist of granite and gneiss (see **Figure 1**), often appearing as domed slabs on hillsides (Nkouathio, 2006).

2.2. Materials

Potential study and sampling sites were selected based on soil parent rock type, and sampling was carried out along road cut sections. The study focused on three types of lateritic soils: soils formed on basalt (Tsinkop), soils developed on granite (Athoumeto), and soils derived from gneiss (Keleng). Fieldwork helped identify, select, and describe different soil profiles following Maignien (1980). **Figure 2(a)** shows a soil profile on granite with coordinates (N05˚25'56.1"; E010˚03'23.6"), and an altitude of 1342 m. This profile is well-developed, with a total thickness of approximately 290 cm, divided into two alteration layers: an upper layer (about 40 cm thick, consisting of fine, loosely compacted, dark soil (10YR/2/1) with a

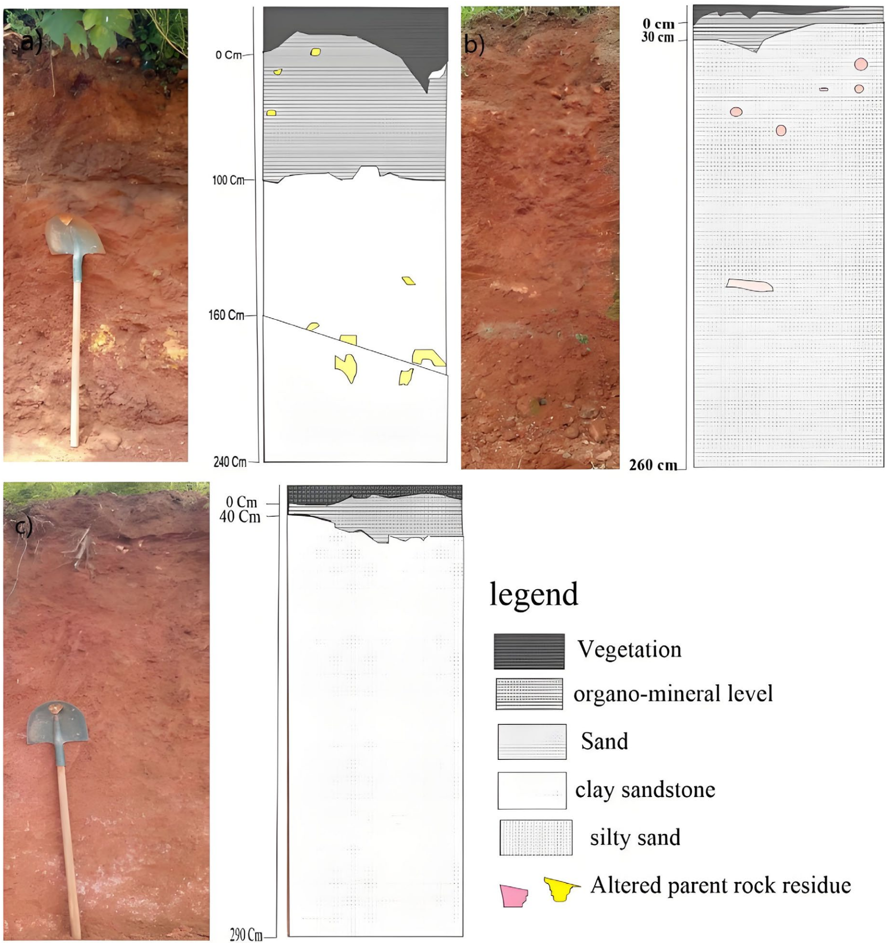

Figure 2. Different soil profiles: a) Soil profiles developed on basalt; b) Soil profiles developed on gneiss; c) Soil profiles developed on granite.

sandy-clay texture and polyhedral-fine structure) and a lower layer (a compact, reddish soil about 250 cm thick with sandy-clay texture and medium-polyhedral structure). **Figure 2(b)** depicts a gneiss-derived lateritic soil profile with coordinates (N05˚26'53.2"; E010˚05'3.3"), and an altitude of 1483 m. This profile is roughly 260 cm thick, featuring two layers: a top layer (around 30 cm, black, with sandy-loamy texture and fine polyhedral structure) and a bottom layer (about 230 cm, with sandy-clay texture and massive structure). **Figure 2(c)** shows a basalt-derived soil profile with coordinates (N05˚26'51.6"; E010˚03'50.9"), and an altitude of 1390 m. It measures approximately 240 cm and has three layers: the top layer (around 100 cm, dark, not very compact, with a coarse silty-sandy texture and fine polyhedral structure), the middle layer (60 cm, reddish alloterite with coarse yellow-ochre elements making up about 10%, sandy texture, and medium polyhedral structure), and the lowest layer (80 cm, reddish with yellow patches, silty-clayey texture, and medium polyhedral structure). The boundary between the middle and lower layers is clear and undulating.

At the end of this fieldwork, nine samples, each weighing approximately 10 kg, were selected from three different parent rock locations and subjected to initial geotechnical laboratory tests, including particle size analysis, Atterberg limits, specific gravity, and water content. The liquid limit was measured using the Fall cone penetrometer and the Casagrande apparatus on samples from six sites (quarries and road trenches). A total of 133 samples were collected, consisting of 45 samples from lateritic soils developed on granites, 45 from lateritic soils on gneisses, and 43 from lateritic soils on basalts (**Figure 1**).

2.3. Methods

2.3.1. Analysis of the Soil Physical Parameters

Water content was determined using the standard (NF P 94-050, 1995). This involved weighing a sample, placing it in an oven at 105˚C for 24 hours, and then re-weighing it to find the mass of water lost. The water content was then calculated as the ratio of the water mass to the soil solids mass. The specific gravity was measured by determining the clean volume of the grains, excluding voids, and calculating the ratio of weight to volume, following the standard (NF P 94-054, 1991). Granulometric analysis was performed by wet sieving the materials according to the standard (NF P 94-056, 1996). Plastic limits were determined using the roller technique according to the standard (NF P 94-051, 1993). The liquid limit (LL) was assessed using the Casagrande cup device, which determines the water content at which a groove in the soil paste in the cup closes after repeated blows. The Fall cone penetrometer test was conducted following the standard (NF P 94-052-1, 1995), measuring the cone's penetration under its weight into a soil sample after a specified time. Both the Casagrande device and the Fall cone were obtained from the same manufacturer. The Fall cone penetrometer device consists of a metal cone with a 30˚ apex and a total mass of 80 grams (including the cone and holder). The prepared soil paste was placed in a standard cylindrical cup, and the cone was released vertically onto the paste surface. The penetration depth was measured after a 5-second free fall. The liquid limit was determined by interpolating the water content at a standard penetration depth of 17 mm. All equipment was calibrated before testing, and measurements were repeated at least four times for each sample to ensure consistency of results.

2.3.2. Statistical Analysis

Data processing was performed using Microsoft Excel and SPSS version 29. The Student's t-test was employed to compare the means of two independent samples. To evaluate the results of LLc and LLp measurements at different sites and determine which method was more effective and thus advisable, a homogeneity of variances test (F-test) and the calculated Student's t-test were conducted. The t-test results were compared with the theoretical value obtained from Student's t-table at the 5% significance level.

Formulation of the hypotheses

H_0: There is no difference in the means of the two measurements carried out using the Casagrande device and the Fall cone apparatus. $H_0 : \mu_1 - \mu_2 = 0$.

H_1: There is a difference in the means of the two measurements carried out using the Casagrande device and the Fall cone apparatus. $H_0 : \mu_1 - \mu_2 \neq 0$ (Two-Tailed Hypothesis).

3. Results

3.1. Geotechnical Characterization of Soils

The results of the preliminary analysis of the lateritic soils developed on basalt, granite, and gneiss are provided in Table 1 and Table 2. Table 1 shows the geotechnical parameters such as the Atterberg limits, specific gravity, and water content. Table 2 displays the size fractions and classifications.

Table 1. Results of geotechnical parameters of the different soils.

Rock substratum	Basalte				Granite				Gneiss			
Geotechnical parameter	**PB1**	**PB2**	**PB3**	**Avg**	**PG1**	**PG2**	**PG3**	**Avg**	**PGn1**	**PGn2**	**PGn3**	**Avg**
LL	79	71	80.10	**76.7**	49	46.1	45.3	**46.80**	51.36	55.98	52.8	**53.38**
PL	34.22	46.6	52.74	**44.51**	32.89	28.98	28.3	**30.06**	30.65	36.09	24.95	**30.56**
PI	44.78	24.4	27.36	**32.19**	16.11	17.12	17	**16.74**	20.71	19.89	27.85	**22.82**
CI	1.47	2.62	1.96	**2.02**	2.07	1.07	1.51	**1.55**	1.38	1.84	1.17	**1.46**
specific gravity	3.37	2.15	2.27	**2.59**	2.64	2.79	1.80	**2.41**	2.57	2.02	1.84	**2.14**
Water content	13.25	6.99	26.39	**15.54**	15.69	27.76	19.64	**21.03**	22.68	19.42	20.22	**20.77**

3.1.1. Atterberg Limits

In the basaltic site, the liquid limit ranges from 79% to 80.1%. The plastic limit varies from 34.22% to 52.74%, and the plasticity index ranges from 24.4% to 44.78%. In the granitic and gneissic substrates, the different consistency parameters are similar. The liquid limit ranges from 45.3% to 49% in the granitic substrate and from 51.36% to 55.98% in the gneissic substrate. The plasticity ranges from 28.3% to 32.89% in the granitic site and from 24.95% to 36.09% in the gneissic substrate. The plasticity index varies from 16.11% to 17.12% in the granite substrate and from 19.89% to 27.85% in the gneissic substrate.

3.1.2. Water Content

The results recorded in Table 1 show that the water content varies from one type of soil to another; thus, the water content ranges from 15.54% (basaltic substrate) to 21.03% (granitic substrate) via 20.77% (gneissic substrate).

3.1.3. Specific Gravity

The specific gravity values obtained in the laboratory range from 2.15 to 3.37, with an average of 2.59 for soils developed on basalt. This average is close to the value for soils developed on granite, which is 2.41. In these soils, the specific gravity ranges from 1.8 to 2.79. For soils developed on gneiss, the specific gravity varies from 1.84 to 2.57. The lowest average value among the three types of soils is 2.14.

Table 2. Grain size distribution results and classification of soils.

Rock substratum	Basalt				Granite				Gneiss			
Geotechnical parameters	PB1	PB2	PB3	Avg	PG1	PG2	PG3	Avg	PGn1	PGn2	PGn3	Avg
Gravel	38.82	49.8	44.53	44.4	6.42	13.94	15.04	11.8	37.28	35.81	43.21	38,8
Sand	8.77	11.9	11.52	10.7	39.3	29.98	26.76	32.0	36.17	35.57	29.56	33,8
Silt + Clay	52.41	38.3	43.95	44.9	54.28	56.08	58.2	56.2	26.55	28.62	27.23	27,5
Soils classification												
Classification USCS	MH	CH	CH		CL	CL	CL		CH	CH	CH	

CH: High plasticity clay, CL: Low plasticity clays.

3.1.4. Particle size composition

The granulometric analysis made it possible to determine the proportions of particles of each soil material. These proportions, according to the size of the particles, are given in Table 2. On average, soils developed on basalts are mainly composed of gravel and silts + clays. These proportions are respectively 44.4% and 44.9%. Sands are in a small proportion at 10.7%. The lateritic soils developed on granites are mainly composed of silts and clay, with 56.2% and 32% sands, respectively. The proportion of gravel in this case is low, at 11.8%. Meanwhile, lateritic soils developed on gneiss are those where the different particle sizes are represented equally. On average, they are composed of 38.8% gravel, 33.8% sand, and 27.5% silt + clay.

3.2. Results of the SPSS Analysis

3.2.1. Basaltic Substrate

The results of the descriptive statistics for the soils developed on basalt are shown in Table 3, while the outcomes of the statistical analyses on these soils are presented in Table 4.

Table 3. Descriptive statistics on soil developed on basalt.

Testing Type	N	Min	Max	Average	Standard Deviation
LL_C	43	52.55	88.00	67.40	7.90
LL_P	43	50.80	80.10	65.60	7.80

Table 4. Different statistical tests on soil developed on basalt.

	Levene test of equality of variances		t-test for equality of means				
	Fisher	P-value	t	ddl	P-value	DM	95% CI DM
Equal variance assumption	0.021	0.884	1.078	84	0.284	1.8	(−1.5; 5.2)

Comparison of mean measurements of LL_C Vs LL_P on the basaltic site;

H_0: M.LLc = M.LLp, H_1: M.LLc ≠ M.LLp;

T calculated = 1.078; ddl = 84; DM = 1.8; p-value = 0.28; 95% CI DM = (−1.5; 5.2)

The application of the Student t-test to compare the means of two different measurement methods shows that, at 5% significance level, the t-value (1.078) is less than the theoretical critical value. Moreover, the p-value > 0.05 and the 95% confidence interval includes zero, indicating that the observed difference (M.LLc ≠ M.LLp) is not statistically significant. Therefore, the null hypothesis (H_0) is accepted.

The predictive values of LL_P are significant for the lateritic soils developed on the basaltic substrate ($p < 0.05$). The relationship between LLc and LLp on lateritic soils developed on basaltic terrain is shown in **Figure 3** and it is expressed as LLp = 0.7761LLc + 16.501. However, the equation (LLp = 0.78LLc + 16.50, $R^2 = 0.6018$) shows that the coefficient of the LLp measurement is 0.78.

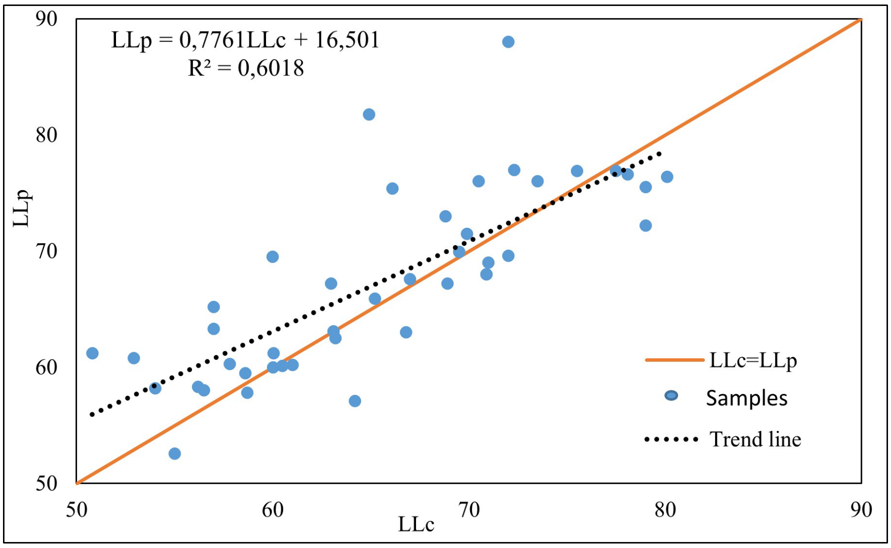

Figure 3. Relationship between LLc and LLp on lateritic soils developed on basaltic terrain.

3.2.2. Granitic Substrate

The results of the descriptive statistics for the soils developed on granite are shown in Table 5, while the results of the statistical analyses on these soils are presented in Table 6.

Table 5. Descriptive statistics on soil developed on granite.

Testing Type	N	Min	Max	Average	Standard Deviation
LL_C	45	43.5	59	51.7	3.9
LL_P	45	43.4	61	50.5	4.2

Table 6. Different statistical tests on soil developed on granite.

	Levene test of equality of variances		t-test for equality of means				
	Fisher	P-value	t	ddl	P-value	DM	95% CI DM
Equal variance assumption	0.224	0.637	1.462	88	0.147	1.2	(-0.4 ; 2.9)

Comparison of mean measurements of LL_C Vs LL_P on a granite site;

H_0: M.LLc = M.LL_P, H1: M.LLc ≠ M.LL_P;

Calculated T = 1.462; df=88; DM = 1.2; p-value = 0.147; 95% CI MD = (−0.4; 2.9).

The application of the Student t-test to compare the means of two different measurement methods shows that, at 5% significance level, the t-value (1.462) is less than the theoretical critical value. Moreover, the p-value > 0.05 and the 95% confidence interval includes zero, indicating that the observed difference (M.LLc ≠ M.LLp) is not statistically significant. Therefore, the null hypothesis (H_0) is accepted.

The predictive values of LL_P are significant for the granite site ($p < 0.05$). The relationship between LLc and LLp on lateritic soils developed on granitic terrain is shown in Figure 4 and it is expressed as LLp = 0.6004 LLc + 21.416. However, for the granitic substrate, the equation shows that the coefficient of the measurement by the LL_P method is 0.60 IU.

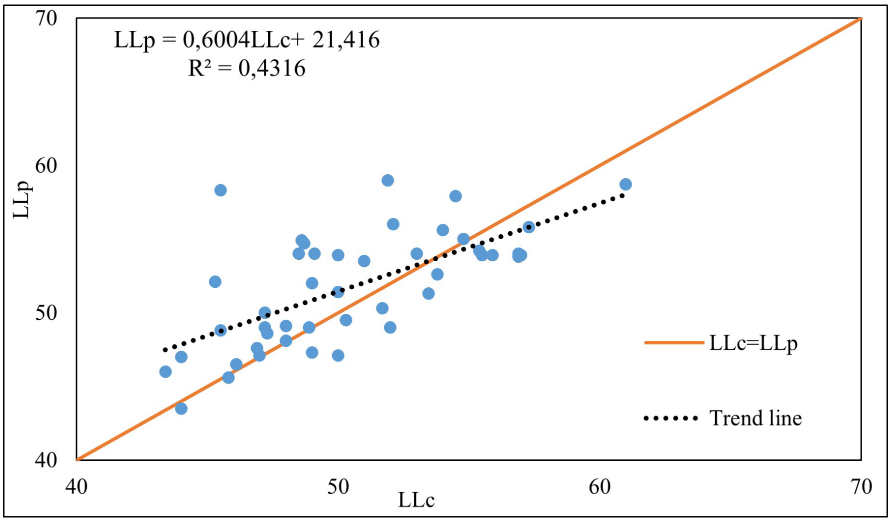

Figure 4. Relationship between LLc and LLp on lateritic soils developed on granitic terrain.

3.2.3. Gneissic Substrate

The results of the descriptive statistics for soils developed on gneiss are shown in Table 7, while the results of the statistical analyses on these soils are presented in Table 8.

Table 7. Descriptive statistics on soil developed on gneiss.

Testing Type	N	Min	Max	Average	Standard Deviation
LL_C	45	44.89	61.2	52.5	3.2
LL_P	45	46	58	52.1	2.8

Table 8. Different statistical tests on soil developed on gneiss.

	Levene test of equality variances		t-test for equality of means				
	Fisher	P-value	T	ddl	P-value	DM	95% CIDM
Equal variance assumption	0.331	0.567	0.693	88	0.490	0.4	(-0.8 ; 1.7)

Comparison of mean measurements of LL_C Vs LL_P on a gneissic terrain;

H_0: M.LLc = M.LLP, H1: M.LLc ≠ M.LLp;

Calculated T = 0.693; df = 88; DM = 0.4; p-value = 0.490; 95% CI MD = (−0.8; 1.7).

The application of the Student t-test to compare the means of two different measurement methods shows that, at 5% significance level, the t-value (0.693) is less than the theoretical critical value. Moreover, the p-value > 0.05 and the 95% confidence interval includes zero, indicating that the observed difference (M.LLc ≠ M.LLp) is not statistically significant. Therefore, the null hypothesis (H_0) is accepted. The relationship between LLc and LLp on lateritic soils developed on gneissic terrain is shown in Figure 5 and it is expressed as LLp = 0.37LLc + 33.07.

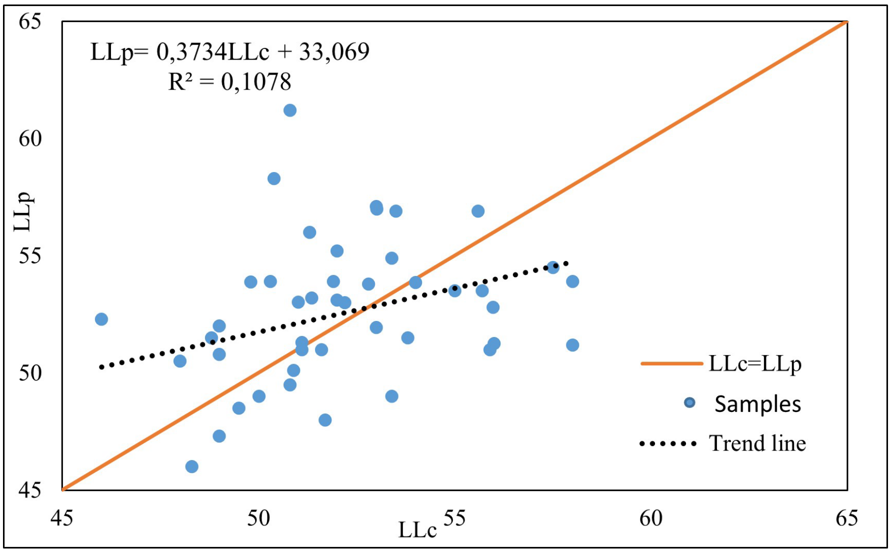

Figure 5. Relationship between LLc and LLp on lateritic soils developed on gneissic terrain.

4. Interpretation and Discussion

4.1. Geotechnical Parameters

4.1.1. Water Content

The results of the preliminary laboratory analysis of the soil samples are presented in **Table 1**. They show that the moisture content of soils formed on basalt was 15.54%, while soils on granite had 21.03%, and soils on gneiss had 20.77%. These average water content values can be explained by the fact that the study area is in a sub-equatorial climate with annual rainfall of nearly 1782.3 mm. Kendjou (2019) studied the fine soils of the Foreké area and found an average water content of 23.07%, which is not much different from the 21.03% average water content. Mafo Wambo (2020) recorded a natural water content of 8.97% in Foreké, which is significantly lower than the 21.03% found in lateritic soils on granite. For lateritic soils on basalt, the water content was 15.54%, much lower than the 20.79% measured at Bamendou on fine laterites on basalt. Still, these values are close to and slightly higher than 13.27%, as reported by Azembong (2019). These differences can be attributed to the fact that water content depends linearly on the hydroclimatic conditions at the time of sampling. Although some researchers, like Keyangue Tchouta (2016), believe that the water content of a material depends on the type and nature of the soil's fine fractions, such as clay minerals like kaolinite, illite, or smectite.

4.1.2. Specific Gravity

The results of the specific gravity of the lateritic soils developed on basaltic terrain were shown in **Table 1** with a value of (2.59), which is higher than that in lateritic soils developed on granite (2.41) as well as lateritic soils developed on gneiss (2.14). The average specific gravity value obtained in basaltic soils is very close to 2.51, obtained on laterites developed on basalt in the Bamendou area by (Mafo Wambo, 2020), and lower than 2.51 obtained on fine Foreké soils by (Kendjou, 2019). For lateritic soils developed on granite, the density obtained is close to 2.46 and slightly lower than that obtained on laterites developed on Foreke-Dschang granite by Mafo Wambo (2020). The results obtained for both sites are close to (2.49 on the basaltic site and 2.39 on the granitic site) those obtained by (Demanou, 2018). According to (De Graft-Jonhson & Bhatia, 1969), the higher the specific gravity, the greater the degree of lateralization. In addition, the higher the clay fraction and alumina (Al_2O_3) content, the lower the apparent density. Thus, lateritic soil samples developed on basalt and granite appear to be the most advanced samples in terms of lateralization processes (ferruginization). Furthermore, the specific gravity of soil particles depends on their chemical compositions. The specific gravity increases with an increase in the iron content and decreases with alumina content, and with the oxidized forms being denser than hydrated forms (Lyon Associates, 1971). It is therefore implying that the lateritic soils developed on basalts are higher in iron oxide content than the other two lateritic soils and conversely lower in alumina, while lateritic soils developed on gneiss are higher in alumina content and lower in iron oxide content than lateritic soils developed on gneiss and granite.

4.1.3. Particle Size Distribution

The various size fractions are summarized in **Table 2**. It can be seen that, on average, lateritic soils developed on basalt are predominantly gravel (44.38%) and silt + clay (44.89%). In comparison, those developed on granite are predominantly silt + clay (56.19%) and sand (32.0%), and those developed on gneiss are predominantly gravels (38.76%) and sand (33.77%). These results are broadly consistent with observations made in the field, as shown in **Figure 2**. The various soil profiles developed on basalt showed the residues of the parent rock with a finer texture (silty) to the touch, hence its high concentration of gravels and fine elements. The profiles of lateritic soils developed on gneiss also showed a high quantity of parent rock residues, except that for the gneiss, the texture contained more sand, which is why the significant soil particle fractions are gravels. The profiles of soils developed on granite, on the other hand, did not have the gravel coarse fraction; instead, they had a slightly finer, sandy texture, resulting in a high concentration of the fine fractions (silts + clays) and sands. The proportion of the various fractions in a soil can vary according to the nature of the parent rock and the intensity of weathering. Since the climate is identical throughout the study area, only the nature of the parent rock can influence the granulometric composition of a soil. Depending on the mineralogical composition of the parent rock, it will be affected to a greater or lesser extent by chemical weathering, and the weathering products formed will differ according to the origin of the parent rock. The high concentration of sands in soils developed on basalt and gneiss is therefore due to the presence of quartz in the various parent rocks, which are minerals that do not alter, while micas and feldspars more often alter into certain fine-grained clay minerals, reason why the lateritic soils developed on basalt and granite have a high proportion of fine fractions (silts + clays).

The percentage of fine fractions (33.77%) obtained on lateritic soils developed on granite is significantly lower than that reported on the lateritic soils of Athoumeto by Kendjou (2019) and Mafo Wambo (2020), which are 54.93% and 64.1%, respectively. Meanwhile, for lateritic soils developed on gneiss, the fine fractions are 27.47%, falling within the range (11% - 42%) of fine fractions reported by Adebisi et al. (2013) on soils developed on gneiss in southwestern Nigeria. These differing observations could be attributed to the position of the profiles and the sampling sites within the profiles.

4.1.4. Atterberg Limits

Atterberg limits are among the most important parameters for assessing a material, mainly used to predict soil behavior and classify it. All the parameter values obtained (liquid limit, plastic limit, plasticity index, and consistency index) on lateritic soils formed on basalt are higher than those on lateritic soils formed on granite and gneiss. The liquid and plastic limits for lateritic soils developed on basalt range from 71% to 80.1% for LL. The plastic limit ranges from 34.22% to 52.74%, while for soils developed on granite and gneiss, these LL values are within the same ranges, but soils on gneiss have higher LL values than those on granite. Specifically, LL ranges from 49% to 45.3% for soils on granite and from 51.36 to 52.8% for soils on gneiss. Regarding the plastic limit, it varies from 28.3% to 32.89% in soils on granite and from 24.95% to 30.65% in soils on gneiss.

The high plastic limit of the lateritic soils developed on basalt can be explained by the fact that the soil factors and rainfall have favored extensive weathering and, consequently, the enrichment of the clay minerals (kaolinite). Given the results, it is evident that lateritic soils developed on basalt contain more clay minerals than those developed on granite and gneiss. These results are also largely influenced by the sample preparation methods, but above all by testing procedures (Gidigasu, 1976), which is why there is considerable variation in values from one site to another despite being on the same parent bedrock.

Regarding the plasticity index, it is higher in lateritic soils developed on basalt (average 32.9) compared to those on granite (16.74) and gneiss (22.82), because the PI increases with clay content. This means that the proportion of fines (silt + clay) in lateritic soils on gneiss (27.46%)—though lower than in soils on granite (56.19%)—contains more clay than silt. Additionally, lateritic soils on granite and gneiss can be classified as ferralitic soils because PI < 25, while soils developed on basalt are ferruginous soils with PI > 25.

Another interesting soil-derived limit is the consistency index Ic, which can be used to describe the susceptibility of certain tropical soils to weathering and erosion. According to **Table 1**, the Ic of lateritic soils developed on basalt ranges from 1.47 to 2.62. In contrast, for lateritic soils developed on granite, it ranges from (1.07 to 2.07), and on lateritic soils developed on gneiss, it ranges from (1.17 to 1.84). These soils can be considered as firm materials, as their consistency indices are relatively high.

Other factors, including the soil fraction, the sample preparation technique used, the chemistry and pH of any water added to the soil sample when preparing the soil paste for analysis (Jang & Santamarina, 2016), can also affect the values of the liquid limit and plastic limit. Additionally, the drying temperature of the samples also influences LL values.

Granulometric analysis and Atterberg limits were used to classify the various samples. According to the LCPC and USCS classification systems, soils formed on basalt and gneiss belong to the high plasticity clay (CH) class. At the same time, those developed on granite are classified as low plasticity clay (CL).

4.1.5. Comparison of LL Values Obtained with the Fall Cone Penetrometer with Those of the Casagrande Device

The liquid limit of 133 soil samples was measured, consisting of 43 samples of lateritic soils on basalt, 45 samples on granite, and 45 samples on gneiss. These were determined using the Casagrande device and the Fall cone penetrometer.

The LLs obtained ranged from 50.8% to 80.1% with the Fall cone penetrometer, while for the Casagrande device, they ranged from 52.55% to 88%, with average values of 65.6% and 67.38%, respectively, for lateritic soils on basalt. For lateritic soils on granite, LLs ranged from 43.4% to 61% with the Fall cone penetrometer and from 43.5% to 59% with the Casagrande device, with average values of 50.48% and 51.72%, respectively. Meanwhile, the LLs for lateritic soils on gneiss ranged from 46% to 58% with the Fall cone penetrometer and from 44.89% to 58.3% with the Casagrande device, with average values of 52.07% and 52.51%, respectively.

The results of the LLs obtained with the Fall cone penetrometer and the Casagrande apparatus vary, whether they are on lateritic soils developed on basalt, granite, or gneiss. The absolute differences between the two devices are estimated at 3.88% on lateritic soils developed on basalt; this difference is similar to what other authors, including some recent ones like Crevelin & Bicalho (2019) and Ibrahim, Krikar, & Noori (2019), have reported, approximately 3%. On lateritic soils developed on granite, the difference is 2.65% and 2.82%. For soils developed on gneiss, although the differences are less than 3%, they are close to the values cited by these different authors.

Therefore, it is certain, as stated by some researchers such as (Budhu, 1985; Christaras, 2009; Özer, 2009; Spagnoli, 2012; El-Shinawi, 2017; Di Matteo et *al.,* 2016; Crevelin & Bicalha, 2019; Ibrahim, Krikar, & Noori, 2019), that the results of LLp are greater than the LLc, which is not completely the case for the studies carried in Dschang, as only 41.86% of the data in lateritic soils developed on basalt showed that the results of LLp values are greater than LLc. For lateritic soils developed on granite, 35.56% of the results showed that LLp is greater than LLc, and for lateritic soils developed on gneiss, 52.77% of the results showed that LLp is greater than LLc. Though these differences are not significant, the evaluation of the different correlations between LLp and LLc for soils developed on basalt revealed that the correlation coefficient of (0.78) is positive and greater than 0.5. The coefficient of determination $R^2 = 0.60$, reveals that there is a strong relationship between the Casagrande device and the Fall cone penetrometer with the relationship expressed as LLp = 0.78LLc + 16.5. Meanwhile, for lateritic soils developed on granite, the coefficient of determination $R^2 = 0.43$, gives a strong and positive relationship between the two devices, expressed as LLp = 0.6 LLc + 21.4. Meanwhile, for lateritic soils developed on gneiss, the correlations are not valid due to the unsatisfactory results of most of the statistical tests obtained, the value of the coefficient of determination $R^2 = 0.1$, indicative of a weak correlation or relationship, and a correlation coefficient of 0.33 was obtained. The different percentages of samples that do not conform to the hypothesis could be explained by the fact that more than half of the different samples for each type of soil have a clay content of less than 50%. According to Budhu (1985), for soils with high plasticity, the LLp is higher than the LLc, while for soils with low plasticity, the Casagrande device provides higher LLs than the Fall cone penetrometer. Therefore, the excellent correlations obtained for lateritic soils developed on basalt and granite could be attributable to their mineralogical compositions. Christaras (2009) believes that the two devices are identical, but the Fall cone penetrometer gives much better results for soils where the clay content is higher. However, for the rest of the samples where the observation was difficult to come by, these were probably soils of medium plasticity (Jain et al., 2021). For soils of low plasticity, the LL determined using the Fall cone penetrometer was higher than with the Casagrande device. The opposite was observed for soils of high plasticity, while in medium plasticity soils, the comparison was not easy to come by. However, El-Shinawi (2017) classifies soils with a LL of 60% as soils of high plasticity, and as such, the LLc is higher than the LLp, while only 37.14% out of 51.42% of the LLp are lower than the LLc, which have a LL of more than 60% for soils developed on basalt. For lateritic soils developed on granite and gneiss, this hypothesis cannot be applied because the maximum LL is less than 60%. Furthermore, the comparison between the Fall cone penetrometer and the Casagrande apparatus on moderately plastic soils is not as easily ascertained (Jain et al., 2021). Presently, we are unable to justify these results, going by the type of cone used, as there is no significant difference between the LLs of the two types of cones (Russian and British) (El-Shinawi, 2017). However, with the Casagrande device, we note a difference between the hard and soft bases (Özer, 2009). The soils developed on gneiss exhibit properties similar to those studied by Goławska et al. (2020), with both methods showing no significant statistical effect on the LL results. In addition, both tests are riddled with errors which can be linked, among other things, to the rough handling of samples and test apparatus, the initial water content, and the time required to carry out the test (Fojtová et al., 2009). Also, the standardization was not identical worldwide, for example the French standard (NF P94-052-1) recommends that the LL obtained with the Fall cone penetrometer corresponds to a penetration of 17 mm which is not the case with other standards such as the (Moroccan standard NM 13.1.012) where the LL corresponds to 20 mm of penetration which most researchers have used (Budhu, 1985; Christaras, 2009; Özer, 2009; Spagnoli, 2012; El-Shinawi, 2017; Di Matteo et *al.,* 2016; Crevelin & Bicalha, 2019; Ibrahim, Krikar, & Noori, 2019). Other authors even think that the standard penetration depth of 20 mm may not be a proper penetration depth for determining the liquid limit for all types of soils and that the value should be 29 mm, especially in soils of high plasticity. This is the objective of the NCCLL penetrometer, which employs new calibration lines for determining the cone penetrometer liquid limit (30˚, 80 g, 29 mm) (Hrubesova et al., 2016). For this study, the penetration depth adopted for the Fall cone penetrometer was 17 mm, while the hard base Casagrande equipment was utilized, where the LLp values are not higher than the LLc values. The non-standardization of LL determination equipment makes comparability between studies difficult, and therefore, a standardized correction of the LL value on a global scale would be difficult.

4.1.6. Influence of Soil Plasticity on the Relationships between the Fall Cone Penetrometer and the Casagrande Device for Determining the LL

This study established relationships between the cone penetrometer (30˚, 80 g; 17 mm) and the Casagrande device for determining the LL. These relationships were evaluated across various types of soils. **Figure 6** and **Figure 7** display the different equations derived from existing literature and those from this study. In both figures, the relationship between the two devices for lateritic soils on gneiss significantly differs from the equations for lateritic soils on basalt and granite, as well as from older equations in the literature. This variation applies to soils with both low and high plasticity. The phase shift can be explained by the differing p-values, which are greater than 0.05, and the unsatisfactory R^2 (determination coefficient) and R (correlation coefficient) values, which are 0.1 and 0.33, respectively.

The relationships between the two devices (Casagrande and Fall cone) are aligned in the same direction and are close to each other. Sometimes, these two relationships even overlap. **Figure 6** shows that these lines are closer together in the zone where the LL is less than 100, and as the LL increases, the lines move apart slightly. The relationships obtained for soils developed on basalt and granite are valid because they are in the same direction as those found in other studies. The relationship for soils on basalt remains closer than for those on granite, which is normal because the determination and correlation coefficients for soils on basalt are higher 0.6 and 0.78 than those for soils on granite, which are 0.43 and 0.66, respectively. When these relationships are plotted on a graph with a maximum LL of 100, the equation for soils on basalt fits more closely than the others, even overlapping the relationship proposed by Niazi et al. (2020) ($y = 0.89X + 4.204$). These two relationships in this study were not very close to the others when LL values reached 200%. In low plasticity soils, these two equations merge with others, especially with those for soils on basalt. However, the curve for soils on granite deviates slightly from the others beyond 65%, with the maximum LL being 61% in soils on granite. This supports the view of Di Matteo (2012), who believes that two relationships cannot be compared unless they are under the same conditions (ranges of LL and types of devices). Therefore, to use a proposed equation, it must be confirmed that they are under the same conditions, including soil plasticity and device configurations. However, correlations cannot be applied arbitrarily, as they depend on soil type and the range of LL values.

When the 133 samples were combined, a clearer relationship between the Fall cone penetrometer and the Casagrande devices emerged (**Figure 8**). Although the P value was not statistically significant, the correlation and determination coefficients are acceptable, at 0.89 and 0.79, respectively. R is positive and greater than 0.5, indicating a positive relationship between the two devices, as shown by the equation $y = 0.9244x + 5.3877$, with a high R^2 value. This result can be used because, according to some authors like Shimobe & Spagnoli (2019), these different soils are all low-plasticity soils since LLmax = 80.1, which is below their threshold of 120%. However, these soils come from different origins. This contrasts with the works of Mishra et al. (2012) and Kollaros (2016), who set their plasticity thresholds at 77% and 70%, respectively. Di Matteo (2012) even sets the threshold between low and high plasticity soils at 50%. Therefore, this equation can be used, but with many caveats, since the LL range does not conform to norms according to other authors, and not all statistical tests have been explored. The sample size may also explain these high coefficients; the larger the population, the more likely the correlation between two variables will be high if it exists.

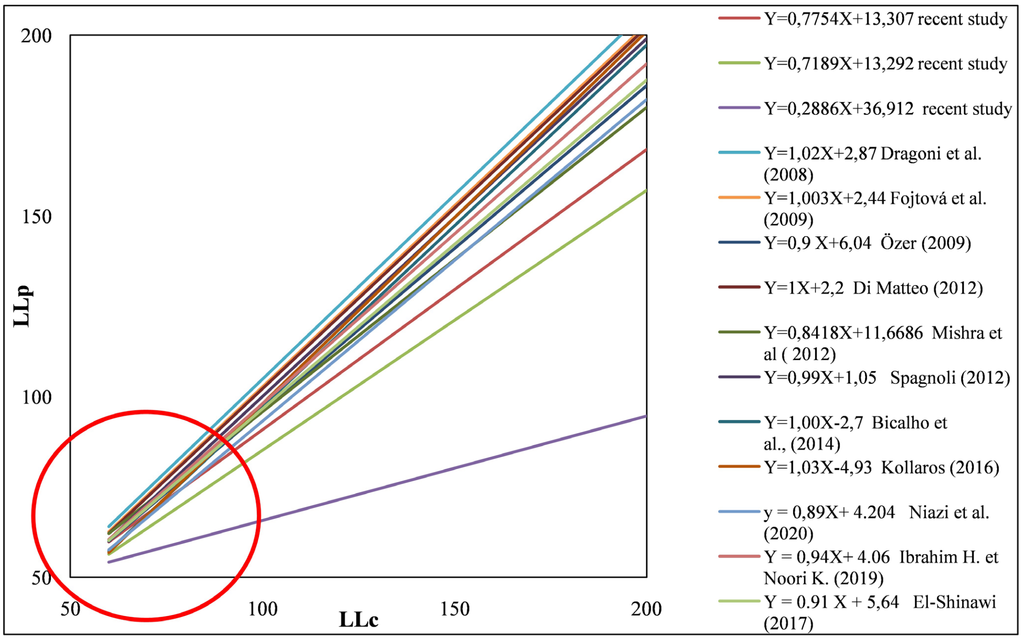

Figure 6. The different correlations between the Casagrande and fall cone for the determination of LL (50 < LL < 200).

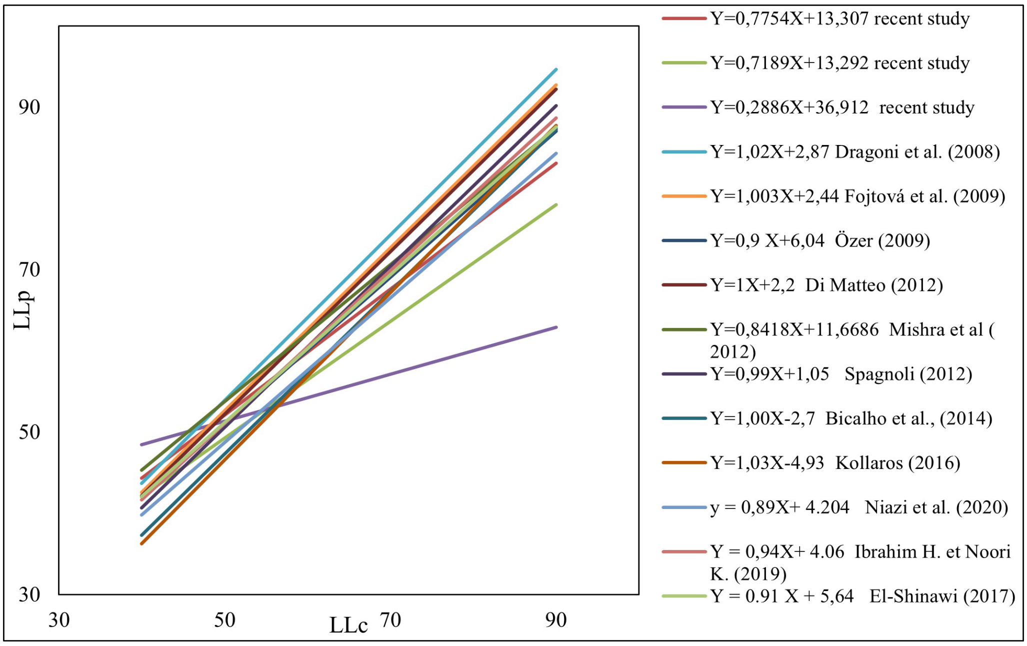

Figure 7. The different correlations between the Casagrande and the Fall cone for the determination of LL (soils of low plasticity 50 < LL < 90).

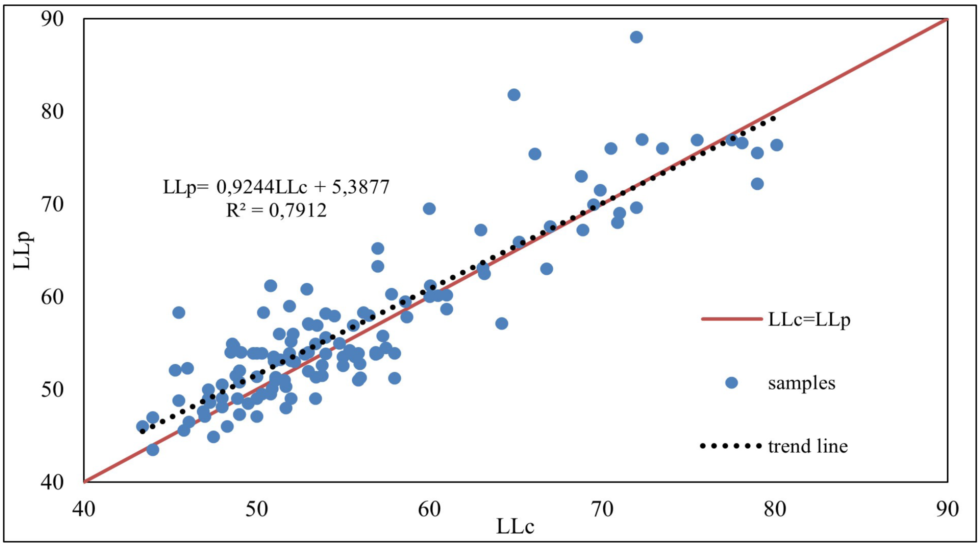

Figure 8. Relationship between LL_c and LL_P on all soils.

5. Conclusion

The present study compared LL values obtained with both the Casagrande and Fall cone penetrometer devices across three types of lateritic soils formed on different basement rocks—basalt, granite, and gneiss. The research was conducted in multiple stages: initial field and sample collection; laboratory analysis; and processing and interpreting the results. The findings showed that soils on basalt, granite, and gneiss display distinct geotechnical characteristics. Soils on basalt have lower water contents, higher specific gravity (2.59), and are dominated by gravel and silt particles, along with high Atterberg limits. Soils on granite mainly consist of silt and clay-sized particles, exhibit the highest water contents, lowest specific gravity (2.41), and lower Atterberg limits. In contrast, soils on gneiss feature a dominance of gravel and sand fractions, with intermediate water contents, and lower specific gravity (2.14), Atterberg limits are similar to those of soils on granite. Statistically, the tests comparing the Casagrande and Fall cone penetrometer devices show no significant difference; however, the Fall cone penetrometer provides more reliable results due to its automatic configuration. Nonetheless, the most appropriate equation relating the two devices was found in soils on basalt, expressed as LLc = 0.78 LLp + 16.5, with a coefficient of determination of 0.60. The strong correlation in soils on basalt is due to their well-graded particle size distribution and high plasticity. Further mineralogical analysis of the soils may be necessary for a more detailed understanding of how these devices relate to soil mineralogy.

Conflicts of Interest

The authors declare that there is no conflict of interest.

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Abbreviations

LLc	Liquid limit determined using Casagrande device
LLp	Liquid limit determined using the Fall cone penetrometer