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Determining undrained shear strength and Atterberg limits simultaneously by an innovative device, Mud Press Machine

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Abstract. The determination of Atterberg limits (LL and PL) holds significant importance in geotechnical studies. Setting of these parameters properly enables important engineering behaviors of soils to be easily predicted. However, these methods have many limitations and uncertainties. These drawbacks of the test methods affect the results significantly. Likewise Atterberg limits, the undrained shear strength (s_u) which represents the total shear strength of soils may also be crucially important in certain geotechnical studies. Determining the s_u of soils is sometimes very challenging, especially for very weak soils due to sampling difficulties. This investigation aims to use the Mud Press Machine with a very significant number of soils to determine the Atterberg limits and s_u simultaneously. For this purpose, 500 sets of tests were carried out on 100 different soil samples with a very wide range of plasticity. Multivariate regression analyses were performed between the force values obtained from the MPM tests and the other three parameters (LL, PL and s_u) obtained from the conventional tests and the relationships between them were examined. Notably high correlations were observed between the MPM results and the conventional tests. The results indicate that the MPM device can determine both the Atterberg limits and undrained shear strength of soils in one simple test and the uncertainties and difficulties in other methods can be overcome with this innovative method.

Keywords: Atterberg limits; fall cone test; mud press machine; undrained shear strength; vane shear test

1. Introduction

Atterberg Limits, namely Liquid Limit (LL) and Plastic Limit (PL), are beneficial parameters for describing the plasticity behavior of fine grained soils. Determining these critical water contents allows one to quickly obtain vital geotechnical engineering parameters such as shear strength, consolidation, compaction and some other deformation characteristics. Atterberg (1911) initially delineated seven water content limits that govern the behavior of cohesive soils. However, only LL and PL are currently used to determine the plasticity and the class of soils.

LL is the critical water content that a soil no longer flows like a viscous liquid. Atterberg (1911) proposed a method for determining the LL of soils based on the number of blows required for a groove in clay to close when the cup was dropped by hand. Subsequently, Casagrande (1932, 1958) introduced an apparatus and a method bearing his name to determine the LL. Despite its widespread use since its invention, this method suffers from various limitations. Numerous investigations have revealed that LL results obtained through the Casagrande apparatus often yield a wide range of values and exhibit poor reproducibility when applied to the same soil. Some of these limitations are summarized as the operator's inexperience, hardness and dimensions of the rubber base, insulation between rubber base and countertop, type of material from which the cup is made, cup's mass and dimensions, the falling height of the cup, falling rate of the cup, type of the grooving tool, wearing of the grooving tool, the tendency of the sliding together of the halves, mobility of the pore water pressure in the dilatant soils, operator judgment for closure length of the halves and maintenance problems (Norman 1958, Johnston and Strohm 1968, Sowers *et al.* 1960, Wroth and Wood 1978, Hanks 1981, Houlsby 1982, Whyte 1982, Lee and Freeman 2007, Kayabali and Tufenkci 2010a, Kayabali and Tufenkci 2010b, Haigh 2012, Kayabali *et al.* 2016, Hrubesova *et al.* 2020, Sands *et al.* 2023).

An alternative method, also widely adopted in practice, is the Fall Cone Test (FC). In the literature, LL values determined through the FC test apparatus are generally regarded as more reliable compared to those obtained via the Casagrande method (Sherwood and Ryley 1968, Sherwood and Ryley 1970, Houlsby 1982, Spagnoli 2012, Kayabali *et al.* 2016, O'Kelly *et al.* 2018, Shimobe and Spagnoli 2019, Díaz *et al.* 2021). The FC method is distinguished by its notable advantages, which include simplicity, ease of execution, and the capability to yield highly reproducible results compared to the Casagrande method (Prakash and Sridharan 2006; Kayabali *et al.* 2016).

Atterberg (1911) defined the PL as the water content of soil between the plastic and semi-solid states where soil cannot be rolled into a thread. This method remains nearly unchanged since Terzaghi (1926) added "the water content at which it starts to crumble at a diameter of 3 mm" to the definition proposed by Atterberg (1911). PL test has many inherent shortcomings that have led to low reproducibility.

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The test relies on determining the limit water content of the soil by rolling it by hand. An alternative method known as plate rolling was introduced to mitigate certain limitations associated with direct hand contact with the soil bead, although it still yields inconsistent results. In plate rolling, the soil bead is rolled using a plate apparatus. However, even with the adoption of the plate rolling technique, the PL test continues to exhibit significant limitations, as documented in various investigations. Some of these limitations of the PL testing are: applied pressure to the soil bead, width of hand contact to bead diameter, friction between soil, hand, and base plate, rolling rate, operator judgment and performance, and contamination risk of the sample studies (Sherwood 1970, Sherwood and Ryley 1970, Whyte 1982, Belviso *et al.* 1985, Sivakumar *et al.* 2009, Nagaraj *et al.* 2012, Kayabali *et al*. 2016, O'Kelly *et al.* 2018, Spagnoli and Feinendegen 2017).

PL test often exhibits significant variability, with results showing discrepancies of up to 12% when the same soil is tested across different laboratories. This underscores the substantial challenges of attaining reproducibility with this test (Sherwood 1970, Sivakumar *et al*. 2015).

Researchers have made several attempts to establish a rational basis for this long-established test method for determining PL (Burmister 1936, Warlam 1936, Uppal 1966, Livneh *et al.* 1970, Gedalleh *et al.* 1974, Russell and Mickle 1970, Nuyens and Kockaerts 1967, Woods 1960, Wroth and Wood 1978, Timar 1974, Whyte 1982, Lee and Freeman 2007, Moreno-Maroto and Alonso-Azcárate 2015, Moreno-Maroto and Alonso-Azcárate 2017). None of these trials had replaced the conventional bead rolling PL determination method. Whyte (1982) suggested that the cone penetrometer and extrusion methods might hold premise for further studies. Although the Fall Cone (FC) test is one of these methods, Prakash and Sridharan (2006) argued that while it provides a PL value, this value may not represent the actual PL due to the method employed for measuring undrained cohesion. This can introduce complexity as to whether the measured value represents undrained cohesion or the PL itself.

Many researchers have made several attempts to determine Atterberg limits in a single test, yet conventional methods are still prevalent and these methods are struggling to find practical applications (Wood and Wroth 1978, Whyte 1982, Lee and Freeman 2007, Kayabali and Tufenkci 2010, Kayabali 2012, Kayabali *et al*. 2015, Kayabali *et al*. 2016, Manafi *et al.* 2022).

Also, determining the undrained shear strength (s_u) is one of the major challenges in geotechnical applications. s_u expresses the total strength conditions of fine grained soils. s_u of soils are particularly essential in certain engineering and geotechnical applications where the loading rate is rapid and there is no time for pore pressure dissipation.

Several in-situ or laboratory tests can be used to determine the undrained shear strength of soils. Under undrained conditions, drainage of pore pressure in a soil is not allowed, and the soil is subjected to rapid loading to obtain undrained strength parameters.

Conventional laboratory tests used to determine s_u also have several drawbacks. The most common method for determining s_u is the unconfined compression test (UCT) of ASTM D2166 and BS 1377. This test is conducted on undisturbed cylindrical specimens. However, obtaining undisturbed samples from very weak soils can pose significant challenges and, in some instances, may be mpracticable.

Another concern when determining s_u using the UCT method is the phenomenon of "barrelling" of the sample, which can complicate the precise identification of the failure point. In instances where the sample exhibits ductile behavior, no distinct failure point is observable, and the sample undergoes a barrel-like deformation. In such cases, the point of failure is typically estimated to occur within a deformation range of 10% to 20% of the total deformation as suggested by the standards (Liu and Evett 2009, ASTM D2166 2016, ASTM D4767 2011). However, it is essential to acknowledge that this assumption may not consistently hold true, as failure could occur earlier and after this specified deformation range. The failure of a silt-clay soil under triaxial tests, for example, occurred in 6% and 12% axial strains, respectively, as shown by Cetin and Gökoğlu (2013). They explained this difference because particles in the drained tests have enough time to respond to the applied shear stresses, which cause failure, and change their orientation accordingly, whereas particles in the undrained tests do not have sufficient length of time to respond to the applied shear stresses, which, in turn, causes a delay in the failure.

Another alternative laboratory test method is the Vane Shear Test (VST). Although this method is widely used and more straightforward than UCT, it can sometimes be time-consuming, laborious and costly. As stated in ASTM D4648 (2016), “the accuracy of this test method depends on the competence of the personnel performing the test and the suitability of the equipment and facilities used”.

Obtaining these three parameters is challenging and time consuming for geotechnical engineering projects. Kayabali and Tufenkci (2010) proposed an extrusion method for determining Atterberg Limits and they achieved 90% accuracy using this device.

Kayabali *et al*. (2016) took the concept of extrusion technique one step further to a Mud Press Machine (MPM) for determining Atterberg limits more realistically than other methods. Researchers showed that MPM device results have good agreement with conventional methods.

This investigation aims to employ the MPM device, which utilizes the direct extrusion technique, to predict the Atterberg Limits as well as s_u of a large number of soil samples through multivariate non-linear regression analysis while simultaneously seeking to enhance the device's usability by increasing the number of specimens and tests conducted in order to achieve better correlation coefficients.

2. Materials and methods

This investigation was conducted on 100 distinct clayey soil samples gathered from various regions of Türkiye with the objective of gaining a comprehensive understanding of soil behavior. The soil samples used in this investigation

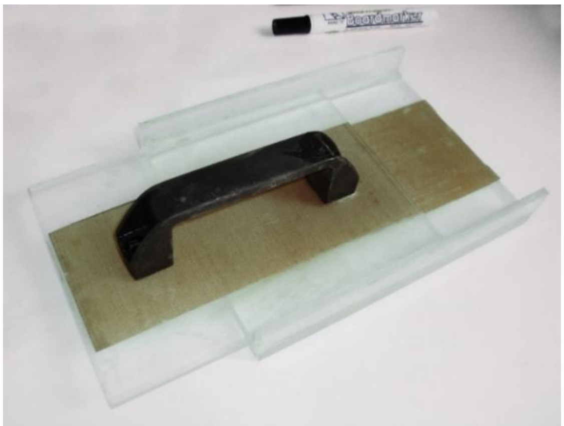

Fig. 1 Plate rolling tool

Fig. 2 Fall cone (FC) test apparatus

were mostly regolith type and of lacustrine origin to a lesser extent. As the standards for LL and PL dictate all soil samples were oven-dried and sieved through #40 sieves prior to laboratory testing. The same soil samples were also used for vane shear and mud press tests.

The plate rolling method, an alternative to hand rolling, as specified in ASTM D4318 (2010), was utilized in this study to conduct PL tests following the guidelines outlined in ASTM D4318 (2017), where a plate rolling apparatus was employed, thereby ensuring that no manual contact occurred with the samples during the testing process (Fig. 1).

LL values were obtained by the FC test device depicted in Fig. 2 according to BS 1377 (BSI 1990); in this way, it avoided most of the operator effects faced by the Casagrande method. In the FC test, an apparatus (Fig. 2), a cone of a total apex angle of 30°±1° fixed to a vertically sliding shaft is positioned with the cone's tip touching the soil's surface to be tested. The total mass of the cone and shaft is 80±0.05 g. The cone is released and penetrates into the soil. The LL is defined as the moisture content of the soil at which the cone penetrates 20 mm from its original position in 5±0.5 seconds. The cone's surface must be smooth, polished, and usually a stainless steel (Houlsby 1982).

Fig. 3 Laboratory type Vane Shear Test (VST) device

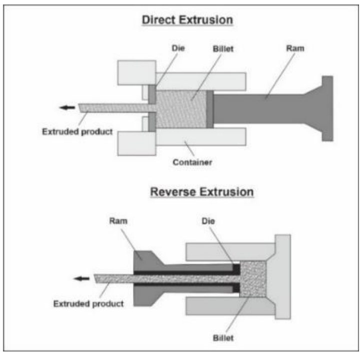

Fig. 4 Schematic direct and reverse extrusion technique diagram

VSTs were performed according to ASTM D4648 (2017). The equipment employed in this investigation comprises four steel rectangular-shaped vanes positioned perpendicular to one another and affixed to a rod. The apparatus is motorized, maintaining a constant rotation rate between 60-90° per minute (Fig. 3). These vanes are inserted into the soil and rotated until failure occurs, with s_u being determined based on the maximum torque recorded at that moment.

2.1 MPM tests

In order to examine the obtainability of these parameters (LL, PL and s_u) with the MPM, extrusion tests were carried out on this device. This device operates based on the direct extrusion method. Direct and reverse extrusion schemes were portrayed in Fig. 4 for comparison purposes only. The employment of direct extrusion in soil mechanics was first done by Timar (1974). The MPM device was developed based on this principle for soil mechanical tests (Kayabali *et al.* 2016). The device has a cylindrical mold with a diameter and height of 30 mm and 28 holes, each measuring 2.5 mm in diameter, located at the bottom of this mold (Fig. 5). The sample placed in this mold at a certain water content is compressed vertically by the loading arm of the device. The soil extrudes from the bottom of the mold in a spaghetti-like form. The device automatically generates a plot of the time versus load curve. The failure load when the moment failure occurs is recorded. The value of force at failure is noted to be used comparatively with LL, PL and s_u.

A total of 100 different soil samples, collected from various locations in Türkiye were used in this investigation.

Table 1 The results of Atterberg limits, mud press tests and vane shear tests

No.	LL	PL	w, %	F_{MPM}, kN	$S_{u\,(VST)}$, kPa	No.	LL	PL	w, %	F_{MPM}, kN	$S_{u\,(VST)}$, kPa
1	51.1	35.9	46.5	0.19	4.7	8	40.0	26.9	35.5	0.15	7.0
1	51.1	35.9	43.2	0.44	21.0	8	40.0	26.9	32.2	0.46	23.4
1	51.1	35.9	42.7	0.62	39.7	8	40.0	26.9	31.5	0.75	42.1
1	51.1	35.9	41.0	0.78	49.1	8	40.0	26.9	29.0	0.91	51.4
1	51.1	35.9	39.3	0.95	65.4	8	40.0	26.9	27.7	1.07	67.8
2	63.0	44.2	53.6	0.20	9.3	9	47.1	29.4	42.4	0.19	7.0
2	63.0	44.2	50.8	0.42	30.4	9	47.1	29.4	36.3	0.54	25.7
2	63.0	44.2	47.7	0.79	53.7	9	47.1	29.4	34.1	0.69	44.4
2	63.0	44.2	46.5	0.98	72.4	9	47.1	29.4	31.6	0.96	60.7
2	63.0	44.2	46.3	1.35	93.5	9	47.1	29.4	29.0	1.18	81.8
3	77.2	44.6	56.6	0.23	16.4	10	41.7	25.6	36.2	0.15	4.7
3	77.2	44.6	52.4	0.42	35.0	10	41.7	25.6	31.9	0.39	16.4
3	77.2	44.6	47.5	0.77	56.1	10	41.7	25.6	30.8	0.61	28.0
3	77.2	44.6	45.8	0.96	60.7	10	41.7	25.6	26.8	0.78	58.4
3	77.2	44.6	42.5	1.35	95.8	10	41.7	25.6	25.7	1.10	72.4
4	32.4	19.3	29.0	0.08	4.9	11	37.0	23.7	33.8	0.15	7.0
4	32.4	19.3	23.0	0.34	19.6	11	37.0	23.7	30.5	0.36	14.0
4	32.4	19.3	22.0	0.54	33.2	11	37.0	23.7	29.0	0.49	32.7
4	32.4	19.3	20.9	0.71	42.3	11	37.0	23.7	27.1	0.75	49.1
4	32.4	19.3	20.0	0.93	57.9	11	37.0	23.7	25.4	1.08	67.8
5	60.4	37.0	54.5	0.18	16.4	12	42.9	25.4	34.5	0.22	9.3
5	60.4	37.0	46.6	0.37	32.7	12	42.9	25.4	30.6	0.42	21.0
5	60.4	37.0	42.0	0.61	58.4	12	42.9	25.4	27.6	0.72	37.4
5	60.4	37.0	41.8	0.77	81.8	12	42.9	25.4	26.0	1.08	67.8
5	60.4	37.0	38.5	0.96	95.8	12	42.9	25.4	24.1	1.18	86.4
6	43.3	25.8	35.1	0.21	7.0	13	36.2	21.6	31.2	0.15	7.0
6	43.3	25.8	31.5	0.41	21.0	13	36.2	21.6	25.2	0.61	25.7
6	43.3	25.8	29.8	0.67	32.7	13	36.2	21.6	23.9	0.79	35.0
6	43.3	25.8	27.5	0.90	51.4	13	36.2	21.6	22.0	1.16	72.4
6	43.3	25.8	25.1	1.17	84.1	13	36.2	21.6	21.1	1.57	88.8
7	41.0	28.0	35.6	0.19	9.3	14	44.5	26.3	35.5	0.24	9.3
7	41.0	28.0	31.4	0.44	28.0	14	44.5	26.3	33.1	0.40	16.4
7	41.0	28.0	31.0	0.60	37.4	14	44.5	26.3	30.4	0.65	30.4
7	41.0	28.0	29.0	0.80	42.1	14	44.5	26.3	28.0	0.84	53.7
7	41.0	28.0	27.7	1.37	100.5	14	44.5	26.3	25.9	1.13	81.8

For each of these 100 soil samples, 5 MPM tests were conducted at different moisture contents, resulting in a total of 500 tests. Multivariate regression analyses were subsequently performed to compare the test results obtained from MPM to conventional ones.

3. Results and discussion

Five LL tests were conducted at five different water contents, the water content versus penetration depth graphs were plotted and the water content corresponding to 20 mm of penetration of the cone was taken as LL. In this manner, a total of 500 FC tests were conducted. The results of fall-cone tests are given in Table 1 along with the other experimental results.

For PLs each of 100 samples were tested five times and the mean of those five values was fixed as the PL.

LL and PL values were found to exhibit a significantly wide range within the set of 100 samples. The LL values ranged from 23 to 106, while PL values ranged from 14 to 74. The classes of 100 different soils were determined in

Table 1 Continued-

No.	LL	PL	w, %	F_{MPM}, kN	s_u (VST), kPa	No.	LL	PL	w, %	F_{MPM}, kN	s_u (VST), kPa
15	51.3	30.5	48.8	0.17	7.0	27	72.9	44.9	64.3	0.18	11.7
15	51.3	30.5	40.9	0.53	25.7	27	72.9	44.9	55.6	0.45	23.4
15	51.3	30.5	35.3	0.76	44.4	27	72.9	44.9	48.4	0.62	30.4
15	51.3	30.5	34.7	0.98	70.1	27	72.9	44.9	46.3	0.77	53.7
15	51.3	30.5	31.0	1.21	88.8	27	72.9	44.9	45.3	0.99	81.8
16	36.0	23.3	36.4	0.14	2.3	28	103	62.2	79.0	0.18	9.3
16	36.0	23.3	29.0	0.27	14.0	28	103	62.2	76.2	0.39	28.0
16	36.0	23.3	22.8	0.80	42.1	28	103	62.2	70.0	0.59	42.1
16	36.0	23.3	23.2	1.23	60.7	28	103	62.2	64.9	0.77	51.4
16	36.0	23.3	22.3	1.59	91.1	28	103	62.2	59.9	0.98	100.5
17	35.0	22.5	36.6	0.16	2.3	29	41.7	26.3	36.6	0.20	7.0
17	35.0	22.5	27.7	0.36	23.4	29	41.7	26.3	33.1	0.39	16.4
17	35.0	22.5	25.8	0.75	35.0	29	41.7	26.3	29.1	0.60	37.4
17	35.0	22.5	24.5	1.16	58.4	29	41.7	26.3	27.3	0.88	60.7
17	35.0	22.5	22.0	1.37	105	29	41.7	26.3	25.4	1.28	79.4
18	41.0	23.9	34.5	0.20	7.0	30	46.1	29.0	39.3	0.20	4.7
18	41.0	23.9	30.9	0.41	16.4	30	46.1	29.0	33.3	0.42	25.7
18	41.0	23.9	29.0	0.60	35.0	30	46.1	29.0	30.9	0.69	51.4
18	41.0	23.9	26.7	0.83	58.4	30	46.1	29.0	28.3	0.93	70.1
18	41.0	23.9	25.4	1.08	84.1	30	46.1	29.0	27.7	1.25	81.8
19	23.3	15.8	24.0	0.08	4.9	31	54.1	33.7	46.3	0.21	9.3
19	23.3	15.8	20.8	0.30	16.4	31	54.1	33.7	38.8	0.54	30.4
19	23.3	15.8	19.6	0.56	34.6	31	54.1	33.7	36.0	0.76	53.7
19	23.3	15.8	16.5	0.78	41.8	31	54.1	33.7	34.3	0.96	72.4
19	23.3	15.8	15.7	0.92	62.4	31	54.1	33.7	32.0	1.18	95.8
20	52.0	29.2	39.3	0.18	9.3	32	56.1	33.6	42.8	0.15	9.3
20	52.0	29.2	37.9	0.57	28.0	32	56.1	33.6	39.4	0.45	32.7
20	52.0	29.2	34.2	0.74	51.4	32	56.1	33.6	34.5	0.81	51.4
20	52.0	29.2	30.5	1.16	74.8	32	56.1	33.6	32.7	1.08	77.1
20	52.0	29.2	29.7	1.54	136	32	56.1	33.6	31.7	1.32	108
21	86.5	47.6	78.5	0.13	7.0	33	51.5	31.2	40.9	0.21	9.3
21	86.5	47.6	71.2	0.40	23.4	33	51.5	31.2	36.2	0.57	30.4
21	86.5	47.6	61.4	0.56	30.4	33	51.5	31.2	32.4	0.78	46.7
21	86.5	47.6	58.5	0.82	53.7	33	51.5	31.2	31.4	0.98	60.7
21	86.5	47.6	50.3	1.04	70.1	33	51.5	31.2	30.3	1.32	79.4
22	46.0	25.9	41.3	0.18	7.0	34	74.7	43.9	57.6	0.29	21.0
22	46.0	25.9	35.8	0.34	21.0	34	74.7	43.9	53.8	0.59	37.4
22	46.0	25.9	31.6	0.70	39.7	34	74.7	43.9	50.1	0.73	56.1
22	46.0	25.9	28.3	0.86	63.1	34	74.7	43.9	46.8	0.83	65.4
22	46.0	25.9	27.0	1.13	79.4	34	74.7	43.9	41.3	1.08	79.4
23	39.6	22.1	35.7	0.15	4.7	35	45.0	24.6	41.9	0.13	4.7
23	39.6	22.1	29.8	0.35	14.0	35	45.0	24.6	35.9	0.26	14.0
23	39.6	22.1	26.7	0.59	35.0	35	45.0	24.6	32.1	0.45	23.4
23	39.6	22.1	24.9	0.78	51.4	35	45.0	24.6	29.6	0.71	42.1
23	39.6	22.1	23.0	0.88	79.4	35	45.0	24.6	27.2	0.82	60.7
24	45.4	24.0	41.5	0.12	4.7	36	68.6	42.8	52.3	0.29	25.7
24	45.4	24.0	33.4	0.29	18.7	36	68.6	42.8	49.6	0.69	46.7
24	45.4	24.0	30.2	0.61	32.7	36	68.6	42.8	47.1	0.83	60.7
24	45.4	24.0	27.4	0.81	51.4	36	68.6	42.8	44.3	1.06	88.8
24	45.4	24.0	25.7	1.18	77.1	36	68.6	42.8	42.2	1.26	103
25	65.6	37.2	54.0	0.18	4.7	37	58.2	39.5	53.4	0.14	9.3
25	65.6	37.2	48.8	0.34	14.0	37	58.2	39.5	48.5	0.37	18.7
25	65.6	37.2	46.1	0.60	32.7	37	58.2	39.5	45.3	0.64	35.0
25	65.6	37.2	42.0	0.75	58.4	37	58.2	39.5	42.1	0.80	60.7
25	65.6	37.2	38.4	0.98	88.8	37	58.2	39.5	39.5	1.08	84.1
26	75.4	40.9	63.0	0.14	7.0	38	60.0	39.8	51.4	0.18	9.3
26	75.4	40.9	56.8	0.34	16.4	38	60.0	39.8	46.5	0.41	21.0
26	75.4	40.9	50.4	0.53	51.4	38	60.0	39.8	43.5	0.74	51.4
26	75.4	40.9	44.3	0.76	67.8	38	60.0	39.8	42.2	1.03	67.8
26	75.4	40.9	41.6	0.96	74.8	38	60.0	39.8	39.8	1.49	88.8

Table 1 Continued-

No.	LL	PL	w, %	F_{MPM}, kN	$S_{u\,(VST)}$, kPa	No.	LL	PL	W, %	F_{MPM}, kN	$S_{u\,(VST)}$, kPa
39	50.4	23.1	45.1	0.16	7.0	51	65.3	31.0	54.7	0.13	4.7
39	50.4	23.1	37.4	0.31	11.7	51	65.3	31.0	46.2	0.31	14.0
39	50.4	23.1	33.2	0.47	21.0	51	65.3	31.0	40.6	0.47	25.7
39	50.4	23.1	30.1	0.61	30.4	51	65.3	31.0	37.4	0.62	35.0
39	50.4	23.1	26.8	1.01	58.4	51	65.3	31.0	32.5	0.85	63.1
40	51.0	30.1	49.0	0.09	2.3	52	57.2	35.4	53.5	0.13	2.3
40	51.0	30.1	43.1	0.26	14.0	52	57.2	35.4	47.2	0.24	11.7
40	51.0	30.1	39.2	0.49	28.0	52	57.2	35.4	41.8	0.53	23.4
40	51.0	30.1	35.8	0.77	44.4	52	57.2	35.4	38.1	0.71	39.7
40	51.0	30.1	34.4	0.88	58.4	52	57.2	35.4	37.6	0.96	58.4
41	95.0	52.1	81.7	0.13	7.0	53	41.6	27.4	41.8	0.16	7.0
41	95.0	52.1	66.5	0.31	21.0	53	41.6	27.4	37.3	0.28	14.0
41	95.0	52.1	60.2	0.44	35.0	53	41.6	27.4	34.2	0.48	23.4
41	95.0	52.1	56.8	0.61	46.7	53	41.6	27.4	31.7	0.70	35.0
41	95.0	52.1	51.8	0.80	58.4	53	41.6	27.4	30.2	0.97	49.1
42	85.0	46.9	78.8	0.11	4.7	54	49.0	33.0	46.8	0.13	4.7
42	85.0	46.9	65.1	0.26	14.0	54	49.0	33.0	41.6	0.26	16.4
42	85.0	46.9	57.9	0.45	30.4	54	49.0	33.0	38.5	0.56	42.1
42	85.0	46.9	53.4	0.66	44.4	54	49.0	33.0	36.9	0.74	56.1
42	85.0	46.9	49.0	0.80	51.4	54	49.0	33.0	36.2	0.96	72.4
43	73.5	46.9	58.2	0.22	14.0	55	44.1	26.8	43.9	0.08	2.3
43	73.5	46.9	55.0	0.45	30.4	55	44.1	26.8	38.6	0.26	9.3
43	73.5	46.9	51.5	0.65	42.1	55	44.1	26.8	34.4	0.58	28.0
43	73.5	46.9	49.8	0.78	63.1	55	44.1	26.8	31.6	0.73	44.4
43	73.5	46.9	47.0	0.98	81.8	55	44.1	26.8	29.7	1.01	63.1
44	71.1	46.0	67.8	0.11	4.7	56	53.5	25.6	43.7	0.09	4.7
44	71.1	46.0	58.7	0.26	11.7	56	53.5	25.6	36.5	0.28	16.4
44	71.1	46.0	51.6	0.57	28.0	56	53.5	25.6	33.3	0.48	35.0
44	71.1	46.0	49.8	0.78	42.1	56	53.5	25.6	31.1	0.67	46.7
44	71.1	46.0	46.3	1.08	51.4	56	53.5	25.6	28.2	0.94	58.4
45	77.8	49.4	69.4	0.20	7.0	57	33.1	19.8	31.4	0.08	4.9
45	77.8	49.4	61.1	0.49	32.7	57	33.1	19.8	25.2	0.29	19.6
45	77.8	49.4	59.2	0.61	49.1	57	33.1	19.8	23.6	0.57	33.2
45	77.8	49.4	58.9	0.88	63.1	57	33.1	19.8	21.7	0.72	42.3
45	77.8	49.4	54.8	1.13	84.1	57	33.1	19.8	19.5	0.88	57.9
46	100.5	62.2	74.9	0.14	9.3	58	38.7	23.8	36.8	0.18	2.3
46	100.5	62.2	72.1	0.35	25.7	58	38.7	23.8	31.5	0.29	11.7
46	100.5	62.2	67.7	0.62	46.7	58	38.7	23.8	29.5	0.52	25.7
46	100.5	62.2	68.0	0.73	58.4	58	38.7	23.8	27.5	0.78	42.1
46	100.5	62.2	64.5	0.98	77.1	58	38.7	23.8	25.2	1.04	74.8
47	48.9	35.7	50.7	0.08	2.3	59	37.5	21.8	32.5	0.23	4.7
47	48.9	35.7	43.0	0.32	18.7	59	37.5	21.8	29.3	0.41	14.0
47	48.9	35.7	42.0	0.43	21.0	59	37.5	21.8	27.4	0.57	25.7
47	48.9	35.7	35.2	0.67	44.4	59	37.5	21.8	26.6	0.78	35.0
47	48.9	35.7	38.0	1.03	67.8	59	37.5	21.8	24.1	1.08	67.8
48	36.8	19.3	33.4	0.11	2.3	60	53.0	31.3	45.9	0.15	4.7
48	36.8	19.3	28.9	0.24	9.3	60	53.0	31.3	40.7	0.33	16.4
48	36.8	19.3	24.0	0.48	30.4	60	53.0	31.3	37.0	0.64	35.0
48	36.8	19.3	21.7	0.74	51.4	60	53.0	31.3	35.3	0.80	44.4
48	36.8	19.3	20.0	1.00	74.8	60	53.0	31.3	34.2	1.03	56.1
49	33.8	18.8	29.2	0.07	4.4	61	90.0	47.9	81.1	0.10	4.7
49	33.8	18.8	24.0	0.25	13.8	61	90.0	47.9	66.3	0.30	18.7
49	33.8	18.8	21.1	0.50	23.6	61	90.0	47.9	60.8	0.51	32.7
49	33.8	18.8	20.0	0.70	42.5	61	90.0	47.9	52.8	0.76	53.7
49	33.8	18.8	19.3	0.98	61.9	61	90.0	47.9	49.9	0.93	63.1
50	32.0	18.8	27.0	0.09	4.7	62	85.1	41.1	71.1	0.13	4.7
50	32.0	18.8	23.4	0.33	18.5	62	85.1	41.1	58.8	0.38	21.0
50	32.0	18.8	21.0	0.55	34.3	62	85.1	41.1	53.2	0.52	28.0
50	32.0	18.8	19.8	0.77	53.7	62	85.1	41.1	51.1	0.71	44.4
50	32.0	18.8	17.9	0.92	57.5	62	85.1	41.1	48.3	0.84	58.4

Table 1 Continued-

No.	LL	PL	w, %	F_{MPM}, kN	s_u (VST), kPa	No.	LL	PL	w, %	F_{MPM}, kN	s_u (VST), kPa
87	54.0	36.5	48.3	0.12	4.7	94	79.8	38.6	74.9	0.09	2.3
87	54.0	36.5	45.0	0.37	21.0	94	79.8	38.6	53.8	0.27	16.4
87	54.0	36.5	42.2	0.61	37.4	94	79.8	38.6	48.5	0.54	37.4
87	54.0	36.5	41.3	0.72	46.7	94	79.8	38.6	43.5	0.77	63.1
87	54.0	36.5	40.1	0.96	88.8	94	79.8	38.6	38.2	1.06	86.4
88	51.4	30.9	45.9	0.12	7.0	95	85.8	41.7	69.0	0.12	7.0
88	51.4	30.9	40.3	0.27	14.0	95	85.8	41.7	59.2	0.28	14.0
88	51.4	30.9	35.1	0.51	35.0	95	85.8	41.7	50.4	0.52	37.4
88	51.4	30.9	32.1	0.75	56.1	95	85.8	41.7	44.2	0.73	60.7
88	51.4	30.9	29.9	0.91	88.8	95	85.8	41.7	38.3	1.08	84.1
89	101.8	66.7	92.0	0.08	4.7	96	86.9	42.4	79.9	0.08	2.3
89	101.8	66.7	80.2	0.30	14.0	96	86.9	42.4	61.1	0.24	14.0
89	101.8	66.7	70.3	0.61	44.4	96	86.9	42.4	53.6	0.51	35.0
89	101.8	66.7	66.8	0.77	56.1	96	86.9	42.4	48.8	0.77	56.1
89	101.8	66.7	63.5	0.89	70.1	96	86.9	42.4	44.1	1.01	63.1
90	70.9	43.2	59.8	0.11	7.0	97	88.0	43.1	75.6	0.09	4.7
90	70.9	43.2	52.0	0.29	18.7	97	88.0	43.1	63.1	0.24	16.4
90	70.9	43.2	42.9	0.56	39.7	97	88.0	43.1	53.3	0.44	35.0
90	70.9	43.2	42.0	0.67	46.7	97	88.0	43.1	44.3	0.77	65.4
90	70.9	43.2	41.3	0.96	60.7	97	88.0	43.1	41.8	1.29	110
91	24.6	14.4	23.5	0.12	2.3	98	90.2	44.4	75.4	0.14	7.0
91	24.6	14.4	19.4	0.29	9.3	98	90.2	44.4	62.5	0.30	18.7
91	24.6	14.4	17.3	0.52	21.0	98	90.2	44.4	56.5	0.43	30.4
91	24.6	14.4	15.9	1.03	32.7	98	90.2	44.4	48.9	0.68	49.1
91	24.6	14.4	14.5	1.18	56.1	98	90.2	44.4	44.7	0.96	81.8
92	25.1	14.4	22.9	0.28	9.3	99	90.8	45.3	84.9	0.08	2.3
92	25.1	14.4	19.7	0.41	23.4	99	90.8	45.3	70.8	0.25	9.3
92	25.1	14.4	18.0	0.61	28.0	99	90.8	45.3	57.4	0.43	30.4
92	25.1	14.4	16.8	0.98	51.4	99	90.8	45.3	60.9	0.78	53.7
92	25.1	14.4	15.6	1.37	67.8	99	90.8	45.3	47.2	0.88	65.4
93	74.0	37.7	76.0	0.10	2.3	100	92.8	46.7	84.3	0.09	4.7
93	74.0	37.7	53.8	0.28	9.3	100	92.8	46.7	72.6	0.23	9.3
93	74.0	37.7	53.4	0.47	21.0	100	92.8	46.7	59.2	0.43	30.4
93	74.0	37.7	45.5	0.62	49.1	100	92.8	46.7	52.2	0.64	49.1
93	74.0	37.7	40.8	1.03	56.1	100	92.8	46.7	47.8	1.03	67.8

Fig. 5 MPM test equipment (a) device and auxiliary components, (b) applying load on the specimen, (c) data reading screen and (d) the spaghetti-like soil specimen after the test

accordance with the Unified Soil Classification System and plotted in the Casagrande Plasticity Chart as shown in Fig. 6. Although the range of LL herein appears to cover most common soils, the range of PL is unusually wide, making this investigation further exclusive.

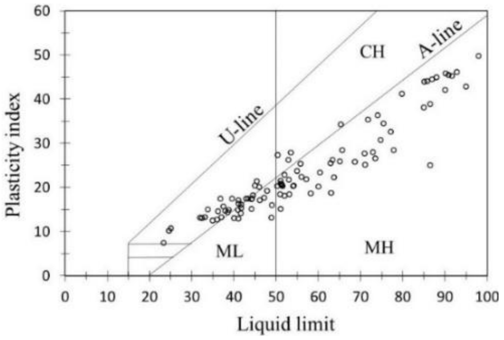

Fig. 6 Classes of the soils used in this study according to the Casagrande Plasticity Chart

Initially, the VSTs were carried out to determine s_u values according to ASTM D4648 (ASTM 2017). Subsequently, on these 100 samples, VSTs were carried out at five different water contents between LL and PL; thus, 500 s_u values were generated.

The specimens initially prepared for the VSTs were subsequently utilized in the MPM tests, ensuring that the samples maintained the same water content (w); thus, 500 MPM force values (F_{MPM}) and 500 water content data were produced through MPM tests.

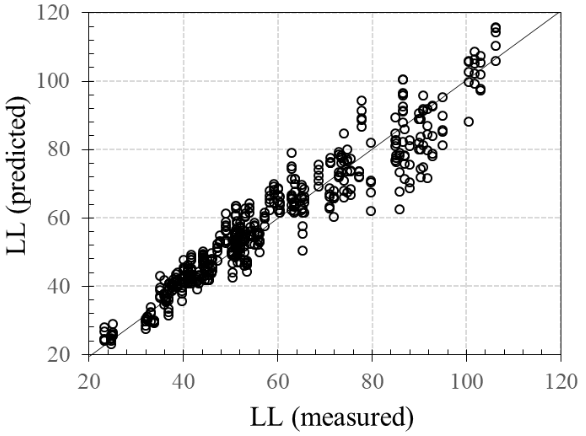

Fig. 7 Relationship between the predicted and experimentally determined LL values

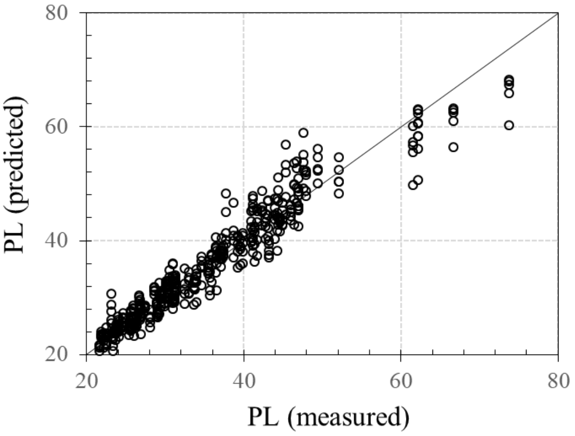

Fig. 8 Relationship between the predicted and experimentally determined PLs

Multivariate linear regression analyses were conducted to explore the relationships between F_{MPM} values and the three other parameters (LL, PL, and s_u) using DATAFIT 9.1.32 (Oakdale Engineering 2014). In these regression analyses, LL, PL, and s_u values were treated as dependent variables, while w and F_{MPM} were kept as independent variables.

Firstly, a multivariate non-linear regression analysis was conducted for LL. Upon examining the analysis results between the values obtained from the traditional FC method and the F_{MPM} values obtained from the MPM device along with the associated moisture content, a correlation coefficient 0.92 was observed between these three sets of values. This coefficient signifies a highly robust relationship when it comes to predicting LL using data from the MPM device (Fig. 7). The regression model relating the LL to F_{MPM} and w is as follows (F is in kN):

$$LL = 1.39(w^{1.04})F^{0.17} \tag{1}$$

A strong correlation is evident when examining the results of the multivariate regression analysis between the PL values obtained from the traditional plate rolling method and the F_{MPM} values obtained from the MPM device along with the associated moisture content. The correlation coefficient between these values was found to be 0.94 and the regression model is

$$PL = 0.83(w^{1.04})F^{0.19} \tag{2}$$

The correlations are particularly pronounced for LL values below 80% and PL values below 60%, indicating higher degrees of correlation below those limits. Nevertheless, a quick glimpse at Figs. 7 and 8 reveals that the predictive equations have a high premise in estimating two major Atterberg limits indirectly. Here it should be emphasized while Kayabali *et al.* (2016) proposed several MPM tests to be performed to plot a semi-logarithmic graph between F_{MPM} and w from which the slope and the y-intercept of the best fit are deduced and thereby the predictive equations of LL and PL were set, this investigation proves that two major Atterberg limits could be determined by running only a single MPM test.

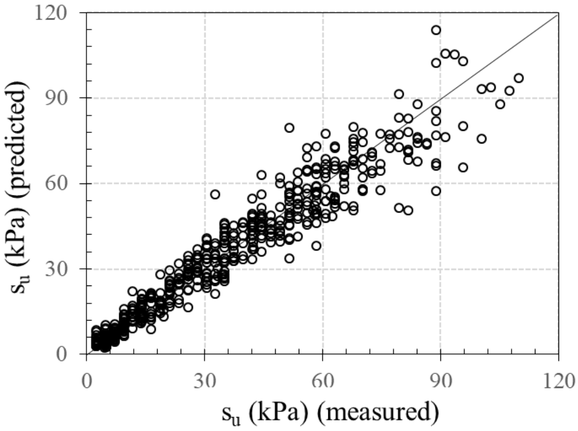

Fig. 9 Relationship between predicted and experimentally determined s_u values

In the similar manner to the two regression analyses above s_u values from the VST, F_{MPM} values from MPM and the associated water content data were subjected to a multivariate non-linear analysis and a very high correlation value ensued. When s_u values from the conventional method exceed 80 kPa, the correlation coefficient has reduced slightly, yet the coefficient is very high for the whole range. As a result of the analysis with 500 tests, the correlation coefficient was obtained as 0.92. (Fig 9). Regression model was obtained as

$$s_u = 25.7(w^{0.27})F^{1.24} \tag{3}$$

3. Conclusions

The MPM device offers several advantages, including reduced operator dependency, avoidance of inherent limitations of traditional test methods, sampling difficulties and the ability to obtain LL, PL and s_u simultaneously in only minutes, excluding the time spent for specimen preparation and oven drying which are also required steps for the conventional tests of LL, PL, and VST.

The results of this investigation involving 500 tests in 100 different soils with an extensive plasticity range (23 < LL < 106 and 14 < PL < 74) resulted in promisingly successful determination of Atterberg limits values. Moreover, with this device, s_u values of very soft soils unsuitable for cylindrical sampling for UCT can be determined. The "barreling" effect, which can be encountered in many kinds of fine-grained soils in UCT, causing uncertainties about the time of failure, is eliminated by the MPM testing method. The correlation coefficients (0.92 for LL, 0.94 for PL, and 0.92 for s_u) obtained with an extensive dataset spanning a wide range of plasticity offer a very high premise to indirectly and simply predict the three important geotechnical parameters by using the MPM apparatus. By this device, Atterberg limits and undrained shear strength results will be determined in a more rational, reproducible and therefore, reliable way in a very short time.

Although this investigation comprises all kinds of fine-grained soils, the CH soils were represented by significantly fewer number of samples than the other three types. A further investigation on CH soils may help to improve the veracity of the proposed technique.

This investigation covered only remolded soils. Further investigation would be very interesting to check the applicability of the proposed approach on undisturbed soils.

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