DEVELOPMENT OF AN ELECTRO-MECHANICAL APPARATUS FOR DETERMINING PLASTIC LIMIT OF SOIL

F.T. Nabil[1], A. Zaman[2], M.Z. Abedin[3]

*[1]Graduating Student, Department of Civil Engineering, Military Institute of Science and Technology, Bangladesh, email: farhannabilftn@gmail.com *Corresponding author*
[2]Graduating Student, Department of Civil Engineering, Military Institute of Science and Technology, Bangladesh, email: anikazaman001@gmail.com
[3]Professor, Department of Civil Engineering, Military Institute of Science and Technology, Bangladesh, email: zabedin5201@gmail.com

Abstract

Plastic limit of fine-grained soil is commonly determined in the laboratory either by the thread rolling method or by the cone penetration method. Despite the fact that these methods of measurement are embraced by many standards around the world, they have been the subject of criticism due to their reproducibility and operator dependency. The present study was conducted aiming to find a method of determination of the plastic limit to overcome these deficiencies. An apparatus was designed and fabricated which could produce soil threads in an electrically operated apparatus. Soil samples from different locations of Bangladesh representing plasticity index (PI) ranging from 5% to 30% were collected and tested using the proposed apparatus as well the conventional methods. Statistical analyses of the data of plastic limits obtained from these sources were done, and good correlations were obtained. A good correlation coefficient (r^2) of 0.85 was obtained while comparing the results of the proposed method with that of thread-rolling method. For the cone penetration method, the correlation coefficient was 0.71. The study, as such, suggests that the proposed method yields close values of plastic limit as compared to those obtained from the conventional methods.

Keywords
Atterberg limits, Plastic limit, Fine-grained soil, Plastic limit apparatus.

1. Introduction

The plastic limit is described as a percentage weight of water with respect to weight of soil solids at the boundary of plastic and semi-solid state of soil mass. In thread rolling method, it is defined as the moisture content at which the soil begins to crumble when rolled into a thread of 3 mm or 1/8th inch in diameter. The standard thread rolling method has been criticized since the operator is required to judge the state of crumbling and the 3-mm diameter of the thread. Different parameters that manipulate the accuracy of measuring plastic limit, such as the pressure applied to the soil thread, the contact area and friction between hand thread, base plate, rate of rolling, etc. cannot be controlled easily and consequently, in the conventional plastic limit method.

Researchers, over the years, have been trying to resolve this issue with alternative approaches. Bobrowski and Griekspoor [1] proposed a plate rolling device claiming to obtain uniform value of plastic limit. However, their experimental findings, along with those of Rashid et al. [2], Ishaque et al. [3], and Rehman et al. [4], independently indicated that the plastic limit using this plate rolling device underestimated their hand-rolling plastic limit values [5]. Gay and Kaiser [6] proposed a motorized rolling device which was later investigated by Kayabali [7] with 120 soil samples and concluded that using the motorized rolling device underestimated the plastic limit obtained from the plate rolling method by approximately 20% [5]. Barnes [8, 9] proposed a technique capable of monitoring the values of indicative toughness to replicate the rolling conditions of soil threads, allowing determination of the plastic limit, had drawbacks in complexity, speed, and criteria employed for plastic limit determination.

Various fall cone approaches have been suggested in search of alternative methods to the hand-rolling plastic limit method. Wood and Wroth [10] proposed cone penetration approach to determine the plastic limit at the moisture content corresponding to 20 mm penetration using 240 g cone. Campbell [11] redefined plastic limit corresponding to the minimum of moisture content of the cone penetration curve using the drop-cone method. There are other different fall cone approaches, such as, using a small specimen ring for fall-cone experiments by Feng [12], Swedish fall cone method by Sharma and Bora [13], and a dual-weight fall cone procedure by Lee and Freeman [14].

However, according to Prakash, Sridharan, and Prasanna [15], due to the viscous shear resistance of diffuse double layer water and the net interparticle attractive interactions between the soil particles, the plastic limit calculated using the fall cone method is not an accurate representation of the undrained cohesion of the soil. Hence, the liquid and plastic limits of the soils determined using the fall cone method cannot accurately represent the plasticity properties of fine-grained soils [15, 16].

This study aims to find an alternative method for determining the plastic limit of soil, overcoming the inconsistencies in results due to the operator sensitivity of the conventional methods.

2. Research Methodology

The present study aims at developing a simple device for determining plastic limit of soil free of operator dependency as happened to the conventional methods. It is considered that the apparatus will produce a soil thread for the determination of plastic limit, warranting the reproducibility of the test results. Details of the apparatus is outlined in the following sections.

2.1 The Apparatus

Figure 1 shows a photograph of the proposed apparatus for determining the plastic limit of soil. It comprises a cylindrical brass frame with an external and internal diameter of 47.5 mm and 35 mm (Fig. 2e) and other components. The apparatus is a modified form of machine that produces vermicelli threads. The interior surface of the frame is rough so that the friction can provide sufficient effective stress to push the specimen forward. The pictures of essential components of the apparatus are shown in Fig. 2. A hopper is permanently attached to the top of the main body to insert molded soil specimen, which can also be referred to as an inlet (Fig 2e). A feed screw (Fig. 2b) welded to a rod made of stainless steel is inserted through the front end of the body, and the stainless-steel rod comes out from the other end and gets attached to a motor. A stainless-steel rod welded to the feed screw is connected to an electrical motor to make the testing procedure more convenient and easy to do by any operator. The AC motor has a capacity of 90 watts and a speed of 40 rpm connected with a 3.5 µF capacitor (Fig 1). The feed screw plates had a diameter of 25.6 mm to 35 mm to penetrate the main body quickly (Fig.2b).

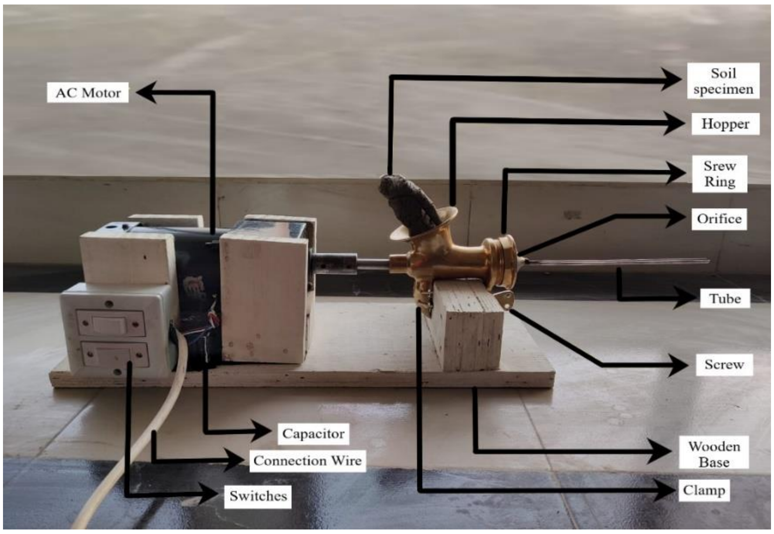

Fig. 1: Plastic limit setup.

The surface of the feed screw was also rough, similar to that of the internal surface of the main body so that the friction could effectively push the mold forward. A stainless steel tube is welded to the 52.6 mm diameter cone-shaped funnel (orifice plate) made of stainless steel (Fig. 2d). The length of the tube is 200 mm. The tube has an internal diameter of 6 mm, and its cross-section is horizontally cut to a semi-circular shape along its length. The internal surface of the funnel is made the smoothest possible so that the soil does not adhere to the orifice. There is a threaded portion at the front part of the body. The funnel is fitted to this threaded portion with the help of a screw ring (Fig. 2c). A wooden base was made to place the motor. The AC motor used can rotate in both clockwise and anti-clockwise directions. Clockwise rotation pushes the soil forward, and anti-clockwise rotation pulls back the soil. Therefore, two individual switches for two different rotation is connected at the wooden base. The body is clamped to the wooden base with a screw (Fig. 1)

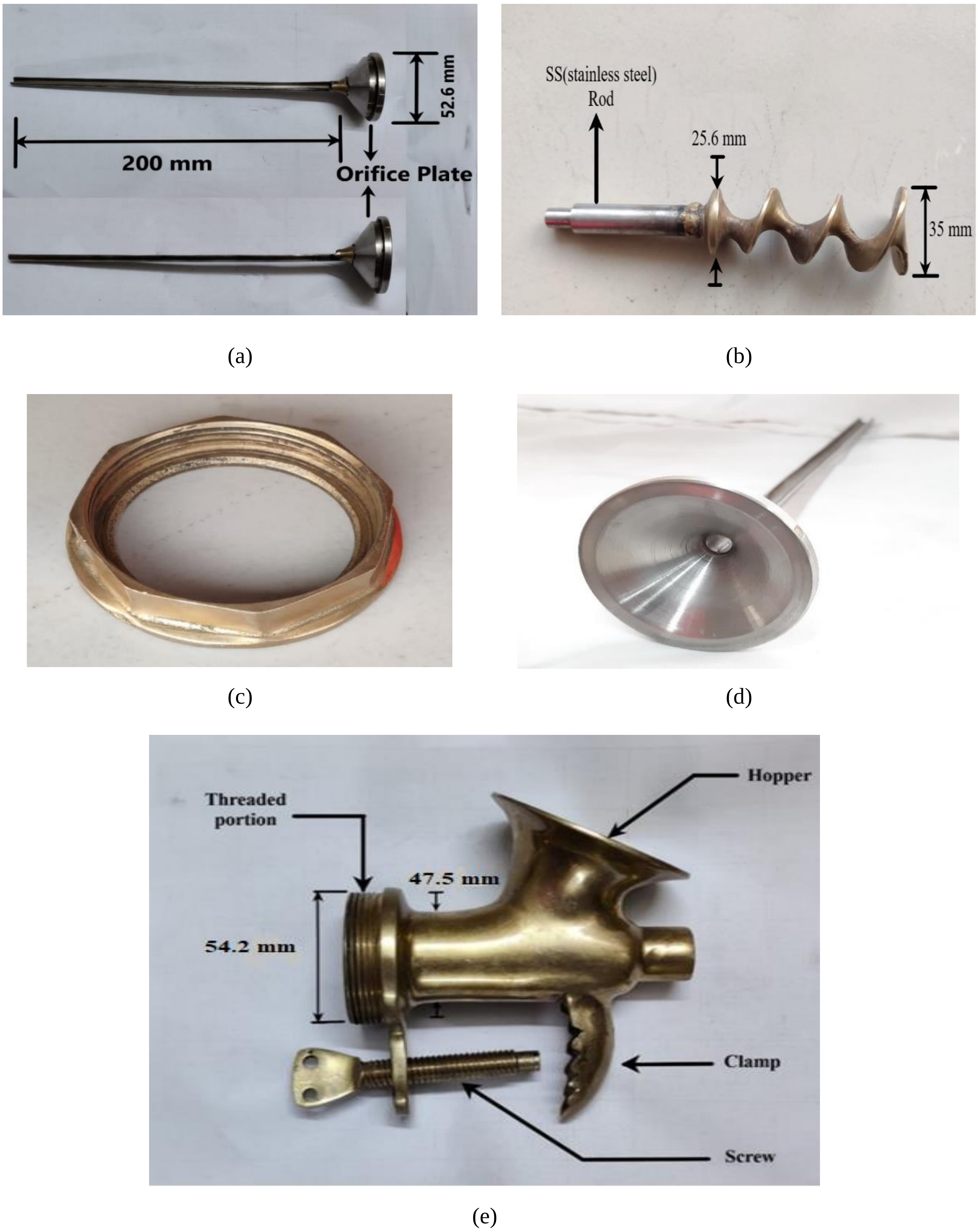

Fig. 2: Components of the plastic limit device; (a) Orifice plate with tube; (b) Feed screw; (c) Screw ring; (d) Orifice plate, and (e) Body or frame.

2.2 Tests Performed

A total of fourteen different soil samples were collected from different locations in Bangladesh. The samples were dried in air and hammered to make soil powder. Physical and index properties of soils like grain size analysis including hydrometer, specific gravity, liquid limit and plastic limit tests were performed at the Geotechnical Engineering laboratory of MIST following the standard ASTM and BSI test procedures. Finally, tests were conducted using the new device to determine the plastic limit of selected soil samples.

2.2.1 Hand-rolling Method of Plastic Limit Determination

Plastic limit of each soil sample was determined using the hand-rolling method according to the procedures of ASTM Standard D4318. Powdered soil was sieved using 425 micron sieve, the finer soil was moistened with water, placed in a humid chamber, and allowed to stay 24 hours for uniform absorption of water. The moist soil was then mixed with further water to make uniform soil paste. A soil ball was made, and placed on a glass plate by rolling with palm of one hand to make a soil thread of 3 mm in diameter. This mixing and rolling process was continued until the thread began to crumble at a diameter of 3 mm. The moisture content of the crumbled portions of the thread was measured. The test should be repeated at least thrice and the average moisture content was taken as the plastic limit.

2.2.2 Cone Penetration Method of Plastic Limit Determination

Wroth and Wood (1978) suggested cone penetration apparatus to determine the plastic limit of soil, as used for liquid limit. This can be done by using a cone of 30° apex angle but with a mass of 240 gm (2.35 N) instead of 80 gm (0.78 N) that is used for liquid limit test. The soil sample preparation procedure is similar to that of hand-rolling method. Three or four tests at varying moisture contents of soil were conducted, and the corresponding cone penetrations were determined. The moisture content corresponding to a cone penetration of 20 mm is the plastic limit.

2.3.3 Determination of Plastic limit Using Proposed New Apparatus

The procedure of soil sample preparation for the proposed method is slightly different than that of the previously mentioned to methods. Sample preparation and test procedures for the newly proposed apparatus is described as under.

Preparation of Test Sample

The air-dried soil samples were disaggregated to powdered form by hammering a rubber-covered pestle. The powdered soil was sieved through a 425-µm (No. 40) Sieve. Approximately 150 g to 200 g of dry soil powder finer than 425-µm was thoroughly mixed with distilled water to have a moisten consistency close to the plastic or stiff state. A cylindrical soil mold, Fig. 3, was prepared using moisten soil for the testing purposes.

In conventional tests, the sample specimen is usually allowed to stay for at least 24 h to ascertain uniform mixing of water with the soil. But in the new mechanical device, the rotation of the feed screw (Fig. 2c) mixes the soil thoroughly inside the body of the device, Fig. 2a, thus saving the test time significantly. As per ASTM D 4318, initially, the mixing time of more than 30 minutes may be needed for stiff, fat clay mold. The cylindrical soil mold used for the test is approximately 200 mm in length and 30 mm in diameter (Fig.3). The following further procedures were followed for the determination of plastic limit.

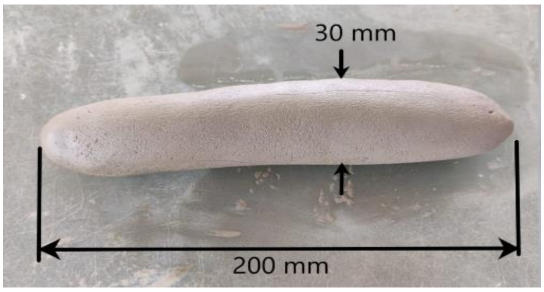

Fig.3: Preparation of soil mold for feeding.

Test Procedure

The test procedure followed for plastic limit using the new plastic limit device is described briefly as under.

(i) A cylindrical mold of soil was taken to feed the hopper of the apparatus and the device was switched on to rotate in the anti-clockwise direction to push the soil mold forward. A thin grease layer was applied on the exit tube to reduce friction.

(ii) The mold was pushed gently into the hopper with the thumb. The soil thread started coming out from the orifice to the exit tube.

(iii) Once the thread reached the end of the tube, a chunk of soil thread was picked up and put back into the hopper.

(iv) Processes (iii) and (iv) were repeated until the soil inside the body reached such consistency that the thread could not be produced with a gentle push into the hopper anymore. Thus, the thread stopped coming out from the orifice.

Fig.4: Cone-shaped specimen sample used to measure the moisture content.

(v) The tube with the orifice was then removed by opening the screw ring. The soil from just behind the orifice that formed the shape of a cone was taken off with a spatula and kept on a container for water content determination (Fig. 4).

(vi) The weight of the container with the specimen sample was recorded and placed in an oven for 24 hours.

(vii) Then the containers were taken out and the dry weight of the specimen was recorded.

(viii) The plastic limit of the soil portions was calculated using the following relation.

$$PL = \frac{W_w}{W_d} \times 100$$

Where, W_w = weight of water; W_d = weight of the oven-dry sample.

3. Results and Discussions

Grain size distribution curves of all the 14 soil samples used in the present investigation are presented in Fig. 5. Table 1 depicts the results of the other physical and index properties of the samples.

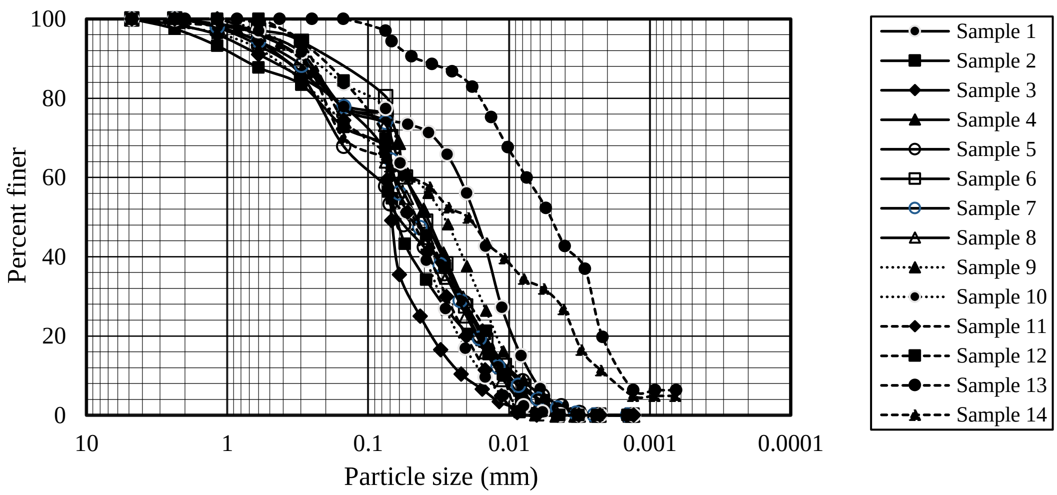

Fig.5: Grain size distribution curves of the soil samples.

Table 1: USCS classification of soil samples

Sample No.	Specific gravity (G_s)	% Passing 0.075 mm sieve	Casgrande liquid limit (%)	Casgrande plastic limit (%)	Plasticity index, PI	USCS soil classification
1	2.62	90	48	22	26	CL
2	2.67	97	48	26	22	CL
3	2.60	86	32	19	14	CL
4	2.62	88	33	21	12	CL
5	2.61	87	36	19	17	CL
6	2.72	92	40	21	19	CL
7	2.43	94	45	22	23	CL
8	2.74	86	33	18	15	CL
9	2.70	95	40	20	20	CL
10	2.80	85	34	18	16	CL
11	2.80	91	45	19	26	CL
12	2.87	85	26	18	9	CL
13	2.71	97	41	29	12	CL
14	2.70	70	30	23	7	CL-ML

Plastic limits were determined using conventional hand-rolling method according to the procedures of ASTM D4318, cone penetration apparatus as per the procedures of BS1377: Part 2, and using the proposed mechanical apparatus. In cone penetration method, for the determination of plastic limit, a cone weight of 240 gm was used as proposed by Wood and Wroth [10], while for the determination of liquid limit 80 gm cone was used. A typical plot for limit and plastic limits for the cone penetration method is shown in Fig. 6. All the results of plastic limits are also presented in Table 2 for comparison purposes.

Table 2: Plastic and liquid limits of soil samples obtained from various methods

Sample No.	Plastic limit (%)			Liquid limit (%)	
	Method			Method	
	Thread rolling	Cone penetration	Proposed apparatus	Casagrande	Cone penetration
1	22	27	22	48	51
2	26	34	28	48	50
3	19	19	18	32	39
4	21	24	19	33	37
5	19	27	19	36	39
6	21	30	23	40	44
7	22	29	23	45	47
8	18	24	19	33	39
9	20	21	22	40	49
10	18	25	17	34	36
11	19	23	17	45	46
12	18	20	15	26	31
13	29	40	28	41	48
14	23	26	22	30	32

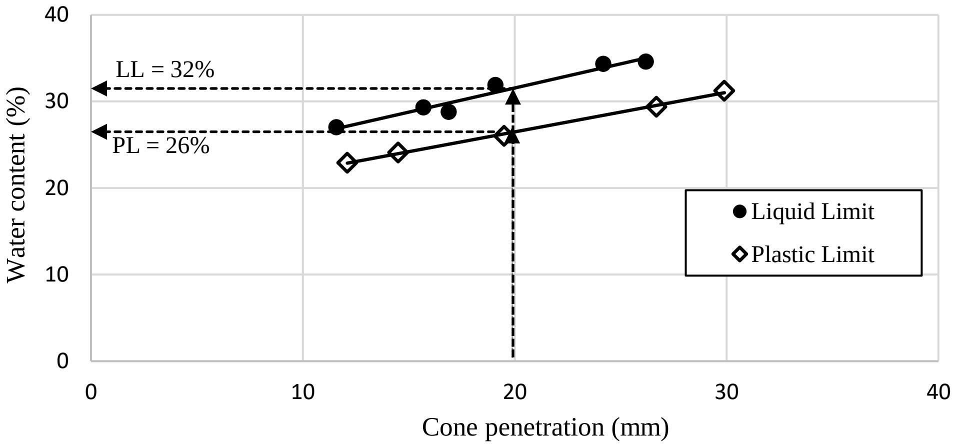

Fig.6: Liquid limit and plastic limit using cone penetrometer (Sample No. 14).

The results of plastic limits as obtained from the proposed method are plotted independently against those obtained from Casagrande and Cone penetration methods in Fig. 7(a) and Fig. 7(b), respectively. A good correlation coefficient ($r^2 = 0.85$) value was obtained while compared to the results of plastic limit as obtained from the proposed method with that of Casagrande method, Fig. 7(a). The corresponding correlation coefficient for the case of cone penetration method is 0.71, Fig. 7(b).

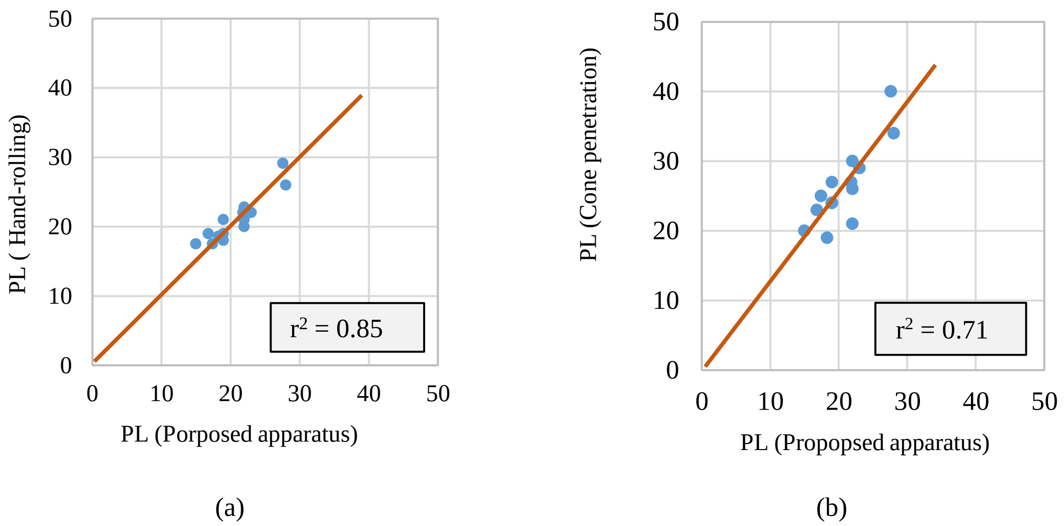

Fig.7: Correlation between plasticity limit (PL) values: (a) Proposed method and hand-rolling method; (b) Proposed method and cone penetration method.

It is to be noted that the soil samples used in the present investigation were limited to low plastic clayey soil (CL as per USCS) only, with liquid limit in the range of 20-50 and plastic limit in the range of 18-40. And the number of samples was limited to 14. Several diameters of soil thread were tried ranging from 3 mm to 6 mm, for the determination of plastic limit. As accordingly cone shaped orifice plate, Fig. 2(d), were fabricated. The 6 mm orifice plate was found to give the best results, generating sufficient momentum to yield the soil threads. The results reported here are a part of an ongoing investigation.

4. Conclusions

The major findings of the study can be outlined as follows.

(i) The newly developed apparatus can measure plastic limit with accuracy and it is free of operator sensitivity.

(ii) As the apparatus has an inbuilt mechanism of mixing soil with water, the determination can be done very quickly as it does not require the mandatory overnight (24 hours) layover time for mixing of soil with water.

(iii) The regression analysis of the data gave very good correlation values ($r^2 = 0.85$) while compared to the results with that of Casagrande's method.

(iv) Further study would be required to generalize the use of the proposed method for all types of soil and also to develop an analytical model as suggested by various authors that at plastic limit, soil possesses a shear strength value of approximately 170 kPa.

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