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Determination of Atterberg limits using newly devised mud press machine

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ABSTRACT

Consistency limits are one of the most prominent parameters to be determined in geotechnical investigations. While these limits are akin to one another, different tools determine each one. Each method of determining consistency limits has its own uncertainties, the operator dependency being the top source of uncertainty. Liquid limit (LL) and plastic limit (PL) tests have a number of uncertainties affecting the test results. The very speculative nature of the bead-rolling method for the plastic limit has long been known. Besides this, its results can be barely accepted as quantitative. In the past, a number of attempts have been made to eliminate these setbacks for Atterberg limits. The scope of this investigation is to evaluate the potential of newly developed "mud press method (MPM)" to predict the two consistency limits. The material employed for this investigation covers 275 soils, whose liquid limits range from 28 to 166. The log(a) and 1/b parameters obtained from the MPM method were correlated to results of the conventional methods. The PL and LL for each soil were predicted using empirical forms and were compared with the laboratory values. Remarkably good matches were obtained between the conventionally determined test results and the predicted values for the liquid and plastic limits. The newly developed tool is superior in several aspects to the available conventional methods and tools.

1. Introduction

The most easily noticeable property of fine-grained soils as the water content changes is probably their variation in consistency, which in turn directly affects their strength. A century has passed since Atterberg proposed the consistency limits in 1911 for agricultural purposes. Commonly known as Atterberg limits, they have become an inherent part of almost all geotechnical investigations on soils, ever since Casagrande standardized them (1932, 1958).

While a series of consistency limits was proposed initially, only the three of them are generally in use: the liquid limit (LL), the plastic limit (PL) and, to a lesser extent, the shrinkage limit (SL). The liquid limit is defined as the water content when a soil becomes sufficiently weak to flow like a fluid. The plastic limit is the water content when the soil is sufficiently stiff so that it becomes brittle and fractures.

There are two methods at present to determine liquid limit of soils. Casagrande's falling cup method (or the percussion method) is included in ASTM standards (ASTM Designation D4318; American Society for Testing Materials, 2005) and still used in much of the world. While they have been pointed out in many investigations in the past, the limitations and/or uncertainties of the Casagrande method are given here for convenience. They include: i) the stiffness of the base rubber, ii) base dimensions, iii) insulation from the supporting table (or bench), iv) material, dimensions and weight of the cup, v) drop height, vi) soil type, vii) frequency of drops, viii) wear of the grooving tool, ix) the tendency of the halves to slide together, x) the migration of water in dilatant soils, xi) operator judgment for closure length of the groove, and xii) maintenance problems (Johnston and Strohm, 1968; Wroth and Wood, 1978; Whyte, 1982; Lee and Freeman, 2007; Kayabali and Tufenkci, 2010; Haigh, 2012).

Because of the limitations and/or uncertainties involved in the percussion method, an alternative method of the fall-cone test was developed to measure the liquid limit. The main advantages of the

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fall-cone method are simplicity, easy operation, and comparative reproducibility (Prakash and Sridharan, 2006). Some researchers such as Wasti and Bezirci (1986), Leroueil and Le Bihan (1996), and Sridharan and Prakash (2000) observed that the liquid limit values obtained from the Casagrande cup method and fall-cone methods are not the same. Prakash and Sridharan (2006) reported that the liquid limit determined from the cone penetration method could differ from that obtained by the percussion method by a margin of about +10% to −200%. In contrary to those assertions, part of the data we used in the present study showed that the match between the liquid limits obtained by the fall-cone method and the liquid limits determined from the Casagrande cup method is perfect, with the exception that the liquid limit measured using the fall cone method slightly overestimates (less than 4% in error) the liquid limit by the percussion method (Fig. 1). Therefore, we opted to use the LL values from the fall-cone method.

We criticize that, while the number of drops is plotted against water content for a given soil in a numerical manner, the Casagrande cup method fails to yield a thoroughly satisfactory rational basis for the liquid limit to rest on because of a number of the parameters affecting the number of blows and thus the low repeatability. In this sense, the fall-cone method has relatively more reliable rational basis, or appears to be a better quantifiable means of achieving the liquid limit.

The present method for determining the plastic limit is the long established thread-rolling (or bead-rolling) test. This procedure subjects the soil to a very complex stress system in that it combines bar rolling distortion, cylinder compression, and lateral extrusion processes (Whyte, 1982; Medhat and Whyte, 1986). The uncertainties related to the factors affecting the test results can be listed as: i) applied pressure to the soil bead, ii) width of hand contact to bead diameter, iii) friction between soil, hand and base plate, iv) speed of rolling, v) personal judgment of the operator, and vi) the risk of contaminating the sample (Whyte, 1982; Sivakumar et al., 2009; Nagaraj et al., 2012). Sherwood (1970) investigated the variations of standard test method results and concluded that clay with an average value of 23% for PL varied from as low as 19% to as high as 39% when tested in several different laboratories. Sivakumar et al. (2009) stated that this method is non-mechanical, and it brings with it some major drawbacks, most notably its subjective nature and the fact that considerable judgment is needed on the part of the operator. Numerous researchers (e.g. Belviso et al., 1985; Wood, 1990; O'Kelly, 2013) have highlighted the relatively poor reproducibility of the Terzaghi's bead-rolling method (Terzaghi, 1926). While the uncertainties involved in bead rolling by hand were somewhat reduced by the substitution of the rolling device (see ASTM D4318; American Society for Testing Materials, 2000), the subjective nature of the test still persists. Therefore, the plastic limit determined using the bead-rolling method is even less quantifiable than the liquid limit obtained from the fall-cone method, and thus weaker rational basis to determine test results on.

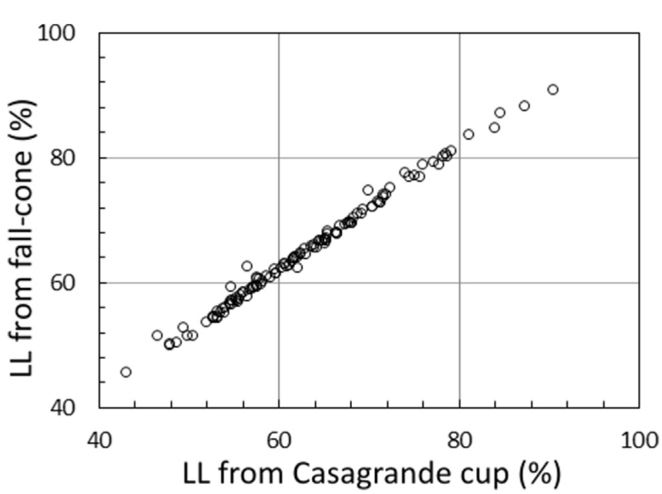

Fig. 1. Plot showing the perfect match between liquid limits obtained from Casagrande and fall-cone methods.

Concerning the non-mechanical or non-quantifiable nature of the thread-rolling test, many attempts have been made to determine the plastic limit on a more rational basis. Most of such attempts have focused on utilizing the fall-cone device to determine the plastic limit as well. In this regard, Feng (2004) showed that the fall-cone method could also be used for determining the plastic limit. Prakash and Sridharan (2006) stated that even though a value of the plastic limit can be obtained using the cone penetration method (even for non-plastic soils), that value does not represent the true plastic limit because of the method used to measure the undrained cohesion, which contributes to soil plasticity. Sivakumar et al. (2009) employed some 24 different soils to test the ability of the standard fall-cone method to determine the plastic limit. They concluded that their new procedure could be used to evaluate PL with reasonable confidence. Timar (1974) introduced the concept of direct extrusion to determine both the LL and PL using the same apparatus. The extrusion method was further investigated by Whyte (1982) to determine the PL. Whyte (1982) showed that the reverse extrusion method is more reliable, which would later be confirmed by additional tests.

Attempts have been also made to determine both consistency limits, namely LL and PL, employing a single tool. In this regard Lee and Freeman (2007) provided an excellent summary of non-ASTM test methods to conduct the Atterberg limits tests. They compared eight non-ASTM test methods for LL and ten non-ASTM test methods for PL, of which seven methods combined LL and PL tests into a single procedure. Whyte (1982) stated that the extrusion method could be established as a method to predict PL, and could be extended to cover liquid limit as well. Kayabali and Tufenkci (2010) took the extrusion method one step forward and proposed that the reverse extrusion method be employed to determine both LL and PL. They redefined the LL and PL as water contents corresponding to specific extrusion pressures. Kayabali (2012) investigated the applicability of the reverse extrusion test for determining the most common Atterberg limits (namely LL and PL), as well as to include the shrinkage limit test. After conducting some 4000 tests, he concluded that about 90% of LL and PL could be predicted with an accuracy of plus/minus 10% error, using the recently introduced soil mechanics testing tool, the reverse extrusion test. He further showed that the shrinkage limits of about 90% of all soil samples tested were predicted within plus/minus 20% error.

In order to combine the LL and PL into a single device, the authors developed equipment called the “mud press machine (MPM).” This newly developed tool is essentially a miniature multi-hole direct extrusion machine. The scope of this investigation is to assess the mud press method as an alternative tool to determine the two consistency limits using only one piece of equipment. Conventional methods are employed to verify the findings from the MPM.

2. Materials

The nature of such an investigation requires the use of soil samples of a wide range of plasticity. A number of both natural soils and those prepared in laboratory were employed. The natural soil samples available in our soil mechanics laboratory had liquid limits ranging from 40 to 80. While this range appears to cover most soils found in nature, it was important to extend the range to ensure that the method proposed is applicable to all variety of soils and those artificial soils prepared in the laboratory were employed. To achieve this goal, bentonite and fine sand were used as additives. To obtain soils with higher plasticity, one of the most abundant soil samples in the laboratory was mixed with bentonite, with varying ratios of dry mass. In this way, soils with a liquid limit of up to 150 were obtained. Similarly, one of the soil samples was mixed with different amounts of fine sand to obtain soil samples with liquid limits below 30. At the end, 275 soil samples were prepared. All soil samples were sieved through #40 mesh prior to conducting the conventional and newly proposed methods of consistency limit tests.

The tool utilized for the liquid limit tests is the fall-cone device with a cone mass of 80 g and an apex angle of 30°. The plastic limit test device comprises the components shown in Fig. 2. The newly devised mud press machine (MPM, Fig. 3) consists of a loadcell of 2 kN, a loading arm, a display screen, and a sufficient quantity of moulds, which are both 30 mm in height and diameter, consisting of 28 equally spaced extrusion channels at the bottom. The diameter of each extrusion channel is 2.5 mm. There is no specific reason for choosing the mould and extrusion channel dimensions. The selected mould dimension simply took into consideration the amount of test material commonly obtained as disturbed samples from the field tests such as the standard penetration test (SPT). The selected extrusion channel diameter was only for the convenience of manufacturing purposes. The spacing between the channels is same as the channel diameter.

Fig. 2. Roll device with the glazing paper for plastic limit tests.

3. Methods

The liquid limit tests were performed in accordance with the BS 1377 (British Standards Institution, 1990). At least five water contents were measured in order to catch the best match between data points and the curve fitted. The plastic limit tests were run, following the guidelines of ASTM D4318. Five to ten trials were employed per soil sample; afterwards, the mean value was taken by dropping the recorded highest and lowest plastic limit values.

As for the mud press method, approximately 150 g of minus #40 dry soil is taken. For the first stage of the test, about 100 g of dry soil is taken and a homogeneous, wet mixture is prepared, whose water content is slightly lower than liquid limit. This is adjusted by experience. Some 10–15 g of wet soil is reserved for the first water content determination. The test mould is filled with wet soil, just by finger pressure. The top of the mould is levelled and wiped by a cloth. The mould is then placed into the slot of the mud press machine. The operator applies a steady force onto the specimen using the lever arm. In the meantime, the device records the applied force for every second and displays it. As the applied force reaches to a certain level, the wet sample extrudes from the channels like spaghetti. At this time, the applied force remains nearly fixed and the display shifts to a flat curve, which gives the intensity of force at the time of extrusion, in other words, failure. The measured values are also recorded in the memory of the device for double-checking the intensity of force at failure. The next step involves the addition of a small amount of dry soil into the previously prepared wet mixture. Again, it is mixed homogeneously to obtain a new specimen with somewhat lower water content than the previous mixture. Another 10–15 g of wet soil is reserved for the second water content determination. The mould is filled with the new wet mixture and a second value of force at the time of failure is obtained. Now, there are two pairs of water content and extrusion force at failure at hand. The procedure is repeated by adding more dry material, mixing homogeneously, and pressing to form spaghetti several more times. The intensity of the force at the time of failure usually ranges from 10 to 100 kgf (i.e., 0.1–1.0 kN). Fig. 4 is a summary of six MPM tests conducted on one soil sample. Data pairs obtained at the end of each series of MPM tests are plotted per soil sample on a semi-logarithmic diagram (Fig. 5). To catch a good match for curve fitting, at least five or six water contents are required. The final stage of the MPM test involves the determination of the slope and y-intercept of the fitted curve. The total duration of time required to conduct an MPM at six different water contents is about 1 h. One point to be highlighted here is about the water content equalization of wet soil mixtures. Regarding this matter, the ASTM D4318 standard suggests that the wet soil mixture is allowed to be stored at least 16 h for the equalization of water content throughout the test sample before the test. However, this requirement appears to be impractical from the standpoint of test duration. In addition, a literature research reveals no investigation about whether or not the omittance of water equalization affects the test results. Therefore, it is not considered to be a significant issue for the tests conducted for the present investigation.

4. Results

To test the usability of the newly proposed technique to determine the consistency limits, 275 soil samples were employed. The experimental results obtained from conventional methods of fall-cone and bead-rolling are presented in Table 1, which also includes MPM data as log(a) and 1/b. The format of the latter was only chosen for practical purposes. A regression analysis was performed employing the log(a) and 1/b parameters as independent variables to obtain the dependent variables of LL. A number of equations relating the log(a) and 1/b parameters to LL were obtained, from the

Fig. 3. Mud press machine deviced for this investigation.

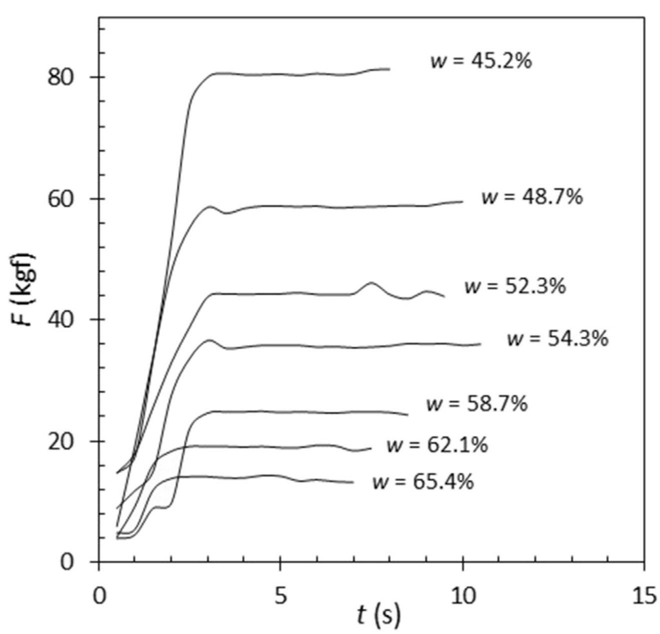

Fig. 4. An example plot for the test results of MPM.

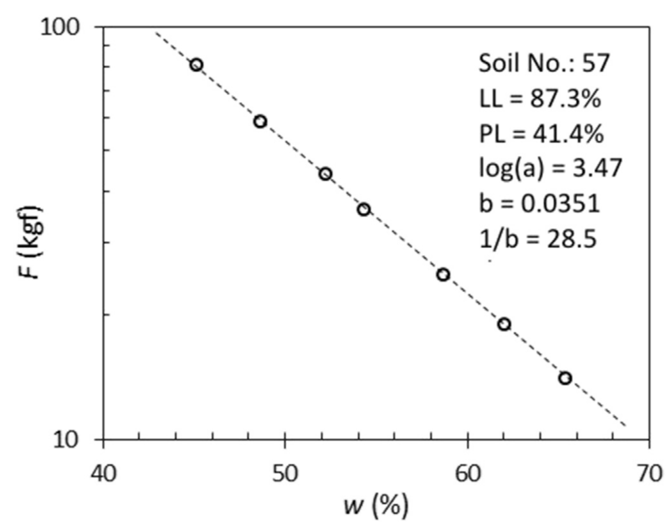

Fig. 5. Semi-logarithmic diagram for the extrusion force at failure versus the water content for MPM test on soil sample 57.

most complex equation to the simplest forms. The most complex correlation equation yielded a regression coefficient (R^2) of 0.96, which showed only a slight change on the third decimal from the following much simpler form:

$$LL = 97.6 + 378\,\log(a) + 3.29^{1/b} \tag{1}$$

The predicted liquid limits using Equation (1) show remarkably good agreement with the experimentally determined liquid limits. Equation (1) predicted 84% of all measured LLs within an error margin of 10%. The mean of the errors with the prediction of LLs is 5.6% with a standard deviation of 4.1%. The plot of the measured versus the predicted LLs is illustrated in Fig. 6.

Another multiple-regression analysis was carried out using the independent parameters of log(a) and 1/b to obtain the dependent parameter of PL. While the most meaningful relationship between log(a) and 1/b and PL yields a regression coefficient of 0.86, it is rather complex, including a number of constants, and is not presented here for practical purposes. Instead, the following much simpler form is opted:

Table 1
Liquid and plastic limits data. LL_m: measured liquid limit, PL_m: measured plastic limit, a: y-intercept of the plotted MPM force (F) versus water content (w) data, b: inverse slope of the F vs. w data, LL_p: predicted liquid limit, PL_p: predicted plastic limit. All LLs and PLs are in percent.

No.	LL_m	PL_m	log(a)	1/b	LL_p	PL_p
1	68.0	29.3	4.00	17.5	60.6	30.2
2	59.6	24.4	3.55	19.2	54.2	26.6
3	62.5	30.0	3.89	18.5	61.2	30.1
4	59.5	25.6	3.43	21.7	58.7	27.7
5	74.9	32.9	3.53	25.5	74.3	32.1
6	74.2	31.8	3.74	23.0	72.1	32.9
7	81.3	33.9	3.07	35.1	89.8	30.9
8	77.8	33.3	3.17	28.8	73.0	29.4
9	77.4	33.1	4.26	19.3	72.4	36.1
10	53.0	29.8	4.36	14.0	56.8	28.4
11	61.0	24.3	2.86	30.4	65.3	26.1
12	71.9	26.6	3.08	26.8	62.9	27.0
13	72.9	40.3	5.01	15.2	72.1	39.6
14	68.3	39.1	4.27	17.0	64.9	33.0
15	63.1	41.3	6.42	9.5	69.9	40.3
16	59.3	29.9	3.33	22.7	58.8	27.3
17	56.1	33.4	3.84	18.4	59.6	29.3
18	54.8	30.5	4.41	13.2	55.2	27.2
19	54.8	25.0	3.25	22.5	55.3	26.1
20	51.7	24.8	3.16	23.4	54.8	25.6
21	63.0	29.9	3.48	23.1	64.9	29.6
22	62.8	28.8	3.45	22.7	62.7	28.9
23	45.8	26.2	3.77	15.8	49.2	24.4
24	68.5	27.2	3.20	25.1	61.9	27.5
25	50.7	28.6	5.56	9.0	59.1	26.3
26	77.0	29.6	2.90	32.8	75.0	27.7
27	60.8	25.3	3.34	22.5	58.3	27.2
28	67.9	33.8	4.96	13.3	65.1	34.7
29	55.4	25.4	4.51	12.3	54.2	26.0
30	57.4	30.9	5.13	11.0	60.0	29.8
31	61.3	24.2	3.25	21.8	52.8	25.4
32	71.3	29.2	3.77	19.5	61.4	29.8
33	56.6	21.9	4.15	13.0	49.3	23.3
34	59.7	29.2	4.19	15.2	57.3	28.8
35	50.2	25.5	5.00	10.0	54.8	24.0
36	79.5	26.5	3.25	26.7	68.9	29.2
37	70.5	31.2	4.13	14.9	54.9	27.4
38	65.5	24.0	3.46	21.1	57.7	27.5
39	50.5	25.0	4.13	15.8	58.0	29.2
40	69.6	37.1	5.60	12.6	71.5	41.3
41	71.3	27.3	4.12	16.5	60.1	30.2
42	60.0	37.0	4.31	16.0	62.5	31.9
43	57.2	25.0	3.69	17.0	51.0	25.3
44	51.8	26.1	4.52	11.5	51.8	23.6
45	59.6	28.5	3.81	17.5	55.9	27.7
46	56.7	30.1	4.24	15.2	58.4	29.5
47	61.6	30.3	3.74	19.7	61.2	29.6
48	58.6	24.2	4.16	14.1	52.9	26.0
49	77.1	35.6	4.12	19.4	69.5	34.3
50	69.2	31.6	3.46	22.2	61.3	28.5
51	73.3	35.8	3.98	20.5	69.9	33.7
52	80.3	38.6	3.94	21.0	70.6	33.7
53	91.1	35.2	3.16	36.4	97.6	32.5
54	73.0	35.7	4.24	17.3	65.2	33.0
55	79.1	35.3	3.50	25.2	72.4	31.5
56	83.8	26.5	2.78	34.0	73.5	26.7
57	87.3	41.4	3.47	28.5	82.3	33.2
58	75.3	40.2	5.05	15.3	73.0	40.4
59	66.8	40.5	4.95	14.7	69.5	37.7
60	66.8	27.3	3.33	24.5	64.6	28.7
61	64.0	30.1	3.50	20.9	58.2	27.8
62	73.9	31.2	3.31	25.3	66.5	29.1
63	58.3	33.7	3.44	22.8	62.7	28.8
64	69.8	27.6	3.22	24.8	61.7	27.5
65	55.4	33.3	5.43	10.6	62.8	32.3
66	79.0	32.0	2.97	30.4	70.2	27.6
67	67.2	30.5	3.85	18.5	60.3	29.7
68	58.7	27.8	3.70	19.0	57.8	28.3
69	64.1	34.0	3.84	19.8	64.2	31.1
70	72.4	29.4	3.25	25.5	65.1	28.4
71	74.3	30.2	3.23	26.4	67.3	28.7
72	53.9	25.2	3.16	22.4	51.6	24.8
73	64.9	27.8	3.57	21.0	60.7	28.8
74	51.8	28.1	4.15	14.6	54.5	27.0
75	80.7	29.1	2.94	31.0	70.9	27.5
76	63.6	35.9	4.76	12.7	60.0	30.5
77	64.7	29.9	3.48	21.0	57.8	27.6
78	56.8	31.3	4.42	13.0	54.8	26.8
79	72.3	43.8	5.60	12.5	71.2	41.0
80	65.8	36.6	4.60	15.7	67.0	35.1
81	64.3	32.0	3.66	19.6	58.6	28.4
82	67.3	30.7	4.08	19.5	69.0	33.9
83	54.8	32.3	4.53	13.1	57.2	28.5
84	64.8	35.3	3.86	19.2	62.9	30.7
85	55.6	32.7	4.65	12.4	56.9	28.1
86	59.1	32.5	3.99	16.7	57.8	28.9
87	60.3	25.6	4.10	15.4	55.9	27.9
88	57.4	30.4	3.64	19.7	58.4	28.3
89	57.4	31.2	4.28	14.5	56.8	28.5
90	59.5	29.9	3.59	20.5	59.5	28.5
91	54.5	30.0	4.91	11.1	57.1	27.3
92	57.9	31.0	4.17	15.0	56.1	28.1
93	57.6	30.8	4.40	14.1	58.1	29.3
94	68.2	39.6	4.90	14.3	67.3	36.2
95	66.8	30.8	4.33	15.4	60.9	31.0
96	69.8	30.2	3.93	17.8	59.9	29.7
97	66.3	31.8	4.25	15.7	60.2	30.5
98	70.0	31.4	3.26	25.0	63.8	28.2
99	66.8	32.9	3.46	22.4	61.9	28.7
100	66.0	30.7	4.40	16.8	67.0	34.4
101	166	31.1	2.44	67.8	166	28.8
102	158	28.0	2.46	65.0	158	28.8
103	153	30.5	2.54	61.4	151	29.4
104	142	26.5	2.46	59.1	138	28.1
105	134	30.8	2.57	56.7	137	29.2
106	131	28.0	2.51	56.8	134	28.4
107	130	29.4	2.50	55.2	128	28.1
108	128	27.3	2.59	50.5	118	28.5
109	113	28.7	2.61	49.2	115	28.5
110	109	27.6	2.67	46.0	107	28.7
111	107	28.1	2.68	44.9	104	28.6
112	101	27.5	2.77	40.2	93.3	28.6
113	90.5	27.8	2.67	43.6	99.3	28.1
114	88.5	26.7	2.74	41.4	95.7	28.5
115	84.5	26.1	2.78	40.0	93.1	28.6
116	80.0	27.8	2.80	36.7	83.2	27.9
117	77.0	26.9	2.84	35.7	81.8	28.1
118	72.0	25.7	2.88	33.0	74.8	27.6
119	67.0	26.1	3.02	29.2	68.4	27.6
120	65.0	26.5	3.14	26.9	65.6	27.9
121	62.8	25.3	3.13	27.1	65.9	27.9
122	60.5	24.7	3.22	24.8	61.7	27.5
123	55.9	26.0	3.35	22.4	58.3	27.3
124	55.0	23.9	3.14	24.8	58.7	26.5
125	53.5	25.6	3.35	22.0	57.0	26.9
126	142	28.2	2.41	63.0	148	27.9
127	138	30.3	2.53	55.1	129	28.4
128	127	28.6	2.44	59.5	138	27.9
129	124	30.0	2.58	52.0	122	28.6
130	123	26.7	2.54	54.0	126	28.4
131	117	28.9	2.59	47.3	107	27.9
132	116	26.0	2.62	49.5	116	28.7
133	106	28.6	2.53	50.5	114	27.7
134	105	29.1	2.57	49.6	113	28.1
135	102	27.8	2.59	46.0	103	27.6
136	95.0	28.1	2.71	42.0	96.1	28.3
137	92.5	26.5	2.75	38.6	87.0	27.8
138	93.0	28.2	2.68	41.1	91.6	27.6
139	83.0	27.3	2.79	38.6	89.0	28.4
140	84.0	26.7	2.74	41.0	94.4	28.4
141	79.5	26.4	2.73	37.0	80.7	27.1
142	75.0	26.4	2.83	35.0	79.0	27.7
143	69.5	25.9	2.99	30.2	70.4	27.7
144	69.0	24.4	3.05	27.5	64.0	27.1
145	62.0	26.0	3.17	26.6	65.7	28.1

(*continued on next page*)

Table 1 (*continued*)

No.	LL_m	PL_m	log(a)	1/b	LL_p	PL_p
146	63.0	24.4	2.97	30.4	70.2	27.6
147	59.4	25.5	3.34	22.8	59.3	27.5
148	57.5	25.4	3.14	23.8	55.4	25.7
149	55.0	24.9	3.13	25.5	60.6	26.8
150	54.5	25.3	3.29	23.1	58.6	27.1
151	51.5	26.3	3.35	21.9	56.7	26.8
152	53.2	23.6	3.35	21.7	56.0	26.6
153	53.5	25.8	3.16	24.0	56.8	26.1
154	51.5	23.8	3.45	19.1	50.8	25.1
155	50.2	25.0	3.48	18.8	50.7	25.1
156	49.6	24.7	3.46	18.8	50.1	24.8
157	49.6	25.1	3.52	18.1	49.6	24.7
158	48.8	23.5	3.54	18.3	50.9	25.2
159	48.1	25.8	3.56	18.0	50.5	25.1
160	44.5	23.0	3.31	20.2	49.7	24.5
161	45.3	22.8	3.22	20.9	48.8	24.1
162	44.2	23.2	3.35	19.7	49.5	24.5
163	45.9	22.9	3.52	17.2	46.7	23.4
164	45.0	23.4	3.18	20.8	47.0	23.5
165	43.5	21.8	3.27	19.3	45.4	23.0
166	44.0	21.0	3.26	19.6	46.0	23.2
167	44.8	20.7	3.36	18.3	45.2	22.9
168	41.2	21.0	3.37	17.1	41.6	21.3
169	42.4	21.6	3.35	18.1	44.2	22.5
170	42.2	21.3	3.51	16.7	44.7	22.5
171	42.0	20.0	3.40	17.3	43.2	22.0
172	39.0	19.5	3.39	17.4	43.2	22.0
173	40.3	19.1	3.30	18.0	42.2	21.7
174	40.0	22.3	3.38	16.8	40.9	20.9
175	37.8	19.5	3.34	16.7	39.2	20.2
176	37.2	19.1	3.48	15.1	38.5	19.2
177	37.0	17.8	3.50	14.9	38.5	19.1
178	36.8	18.9	3.50	14.8	38.2	18.9
179	35.2	18.3	3.30	16.4	36.9	19.2
180	35.3	18.0	3.42	15.0	36.3	18.2
181	34.5	18.6	3.28	16.5	36.5	19.1
182	33.5	18.1	3.31	16.0	35.9	18.6
183	32.9	17.3	3.50	13.9	35.2	16.9
184	33.2	17.2	3.72	12.0	35.4	14.6
185	32.2	16.9	3.76	11.6	35.1	13.8
186	32.2	18.1	3.39	13.7	31.1	15.0
187	30.7	16.4	3.43	13.6	32.0	15.2
188	31.6	16.5	3.44	13.7	32.7	15.6
189	29.3	16.9	3.32	14.5	31.3	15.9
190	30.8	15.4	3.52	13.2	33.4	15.4
191	41.5	22.4	3.91	12.7	42.6	19.2
192	43.4	23.2	3.98	12.9	45.0	20.7
193	42.7	21.1	3.67	15	43.8	21.5
194	44.1	23.2	4.39	11.7	49.9	22.5
195	39.2	21.4	4.12	12.5	46.9	21.4
196	43.3	23.1	4.20	12.7	49.3	23.0
197	48.3	23.2	3.38	18.1	45.2	22.9
198	46.8	25.3	4.04	14	50.0	24.2
199	50.4	25.6	3.98	13.9	48.3	23.2
200	50.0	24.2	3.84	15.6	50.4	24.9
201	52.8	26.3	3.70	17.2	51.9	25.8
202	48.5	24.0	3.90	15.5	51.6	25.5
203	52.9	25.5	3.75	16.9	52.3	26.0
204	53.0	25.5	3.64	18.5	54.5	26.8
205	51.8	23.3	3.13	22.5	50.7	24.5
206	48.5	25.4	4.12	14.9	54.8	27.3
207	53.1	24.6	3.33	19.8	49.1	24.3
208	50.5	24.6	3.88	17	56.0	27.8
209	55.2	25.2	4.05	15.9	56.5	28.2
210	48.1	24.9	3.87	17.2	56.4	28.0
211	54.6	25.3	3.96	16.6	56.7	28.3
212	57.0	26.1	3.55	20.8	59.4	28.4
213	54.5	28.0	4.06	16.1	57.4	28.7
214	55.2	24.9	3.46	22.1	60.9	28.4
215	52.8	27.9	4.06	16.1	57.4	28.7
216	56.3	26.0	3.46	22.1	60.9	28.4
217	60.5	27.6	3.65	20	59.7	28.8
218	62.1	27.9	3.84	18.5	59.9	29.5
219	61.9	26.9	3.89	17.5	57.9	28.7
220	56.2	27.1	3.81	19.5	62.4	30.3
221	60.4	30.7	4.15	15.7	58.1	29.2
222	60.5	27.6	3.89	18	59.5	29.5
223	60.9	31.9	3.63	20.2	59.8	28.8
224	58.7	27.6	3.73	20.2	62.6	30.1
225	63.6	29.1	3.87	18.2	59.7	29.5
226	57.0	27.4	3.60	21	61.6	29.2
227	62.8	31.2	3.98	17.7	60.8	30.2
228	57.2	28.0	4.00	18	62.2	30.9
229	65.5	29.8	3.89	18.5	61.2	30.1
230	61.0	30.0	3.26	25.9	66.7	28.8
231	62.9	29.0	4.11	17	61.5	30.9
232	58.9	29.8	4.31	16.1	62.8	32.0
233	64.5	28.7	4.10	18.2	65.2	32.5
234	61.4	27.7	4.21	16.5	62.0	31.4
235	58.9	31.6	4.30	17.1	65.9	33.5
236	62.0	31.8	4.19	16.6	61.9	31.3
237	61.2	29.3	3.99	18.5	63.6	31.5
238	59.2	30.8	4.46	14.9	61.8	31.7
239	65.6	32.0	4.19	17.4	64.5	32.5
240	59.5	31.0	4.01	18.3	63.4	31.4
241	62.9	31.9	4.18	17.7	65.3	32.9
242	64.3	31.2	3.89	19	62.8	30.8
243	66.3	28.3	3.88	20.5	67.5	32.4
244	67.6	32.4	4.11	17.4	62.8	31.5
245	63.9	29.1	4.21	17.8	66.3	33.4
246	67.6	32.7	4.72	14.1	63.8	33.4
247	60.9	30.3	3.94	19.7	66.4	32.3
248	67.8	32.0	4.41	15.9	64.1	33.0
249	63.2	28.5	3.70	22	67.7	31.5
250	62.2	32.4	3.83	19.9	64.3	31.1
251	64.1	34.2	3.70	22	67.7	31.5
252	63.0	32.1	4.20	17.4	64.8	32.7
253	63.5	29.5	4.11	18.9	67.7	33.6
254	65.6	33.4	4.29	16.7	64.3	32.8
255	64.7	30.5	4.19	18.2	67.2	33.7
256	67.8	35.2	4.11	18.1	65.1	32.5
257	67.2	33.0	3.87	20.7	67.9	32.5
258	68.8	32.6	4.42	16.1	65.0	33.5
259	79.4	38.5	3.96	23.7	80.0	36.4
260	77.1	37.6	3.88	23.1	76.1	34.9
261	80.0	38.7	3.83	24.7	80.1	35.5
262	82.0	37.3	3.47	28.3	81.7	33.1
263	76.7	37.1	3.77	25.6	81.5	35.3
264	77.4	39.8	3.53	27.7	81.5	33.5
265	80.3	37.6	4.20	21.5	78.2	37.6
266	83.3	39.6	3.67	25.3	77.7	33.8
267	76.1	39.7	3.81	24.9	80.2	35.4
268	86.7	37.3	3.37	30	84.0	32.7
269	75.5	39.0	4.32	20.8	78.4	38.5
270	83.9	40.2	3.80	24.6	79.0	35.0
271	75.7	38.9	3.69	27.2	84.5	35.3
272	92.0	37.2	3.58	27.5	82.4	34.1
273	82.2	37.3	3.83	25.6	83.0	36.1
274	92.2	37.0	3.29	33	91.2	33.0
275	83.5	32.5	3.82	25.5	82.4	35.9

$$PL = 3.27 + 13.2a - 453b \quad (2)$$

This equation has a regression coefficient of 0.80. It predicts 76% of all measured PLs within an error margin of 10%. When using the complex equation, the 10% error margin covers 84% of all measured PLs. When using Equation (2), the mean of absolute errors for predicting the PL becomes 6.4% with a standard deviation of 4.4 (they are 5.6% and 4.1%, respectively for the complex equation). The plot of the measured versus the predicted PLs is illustrated in Fig. 7.

5. Conclusions and discussion

The newly developed mud press machine is introduced as an alternative tool to determine the Atterberg limits on a more

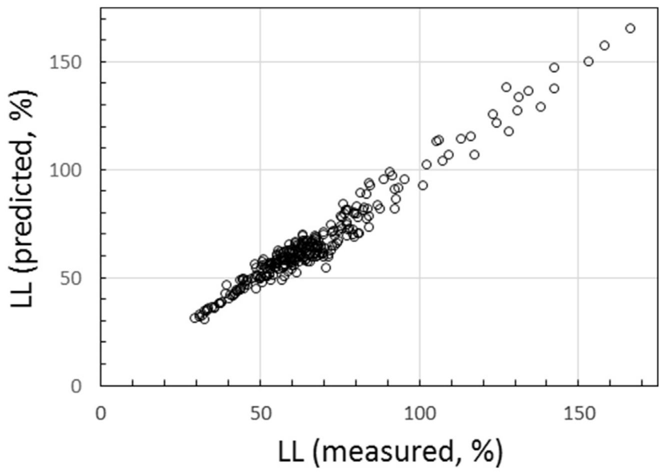

Fig. 6. Plot showing the comparison between the predicted- and experimentally determined LLs.

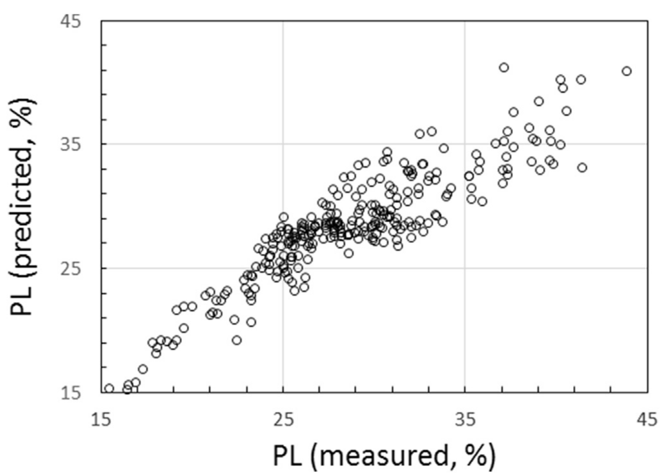

Fig. 7. Plot showing the comparison between the predicted- and experimentally determined PLs.

rational and quantifiable basis. The empirical equations based on the experimental data on some 275 soil samples help determine the liquid limit with a great degree of accuracy. The level of accuracy to predict the plastic limit with the new approach is slightly lower than it is for the liquid limit. The authors attribute this to the very speculative nature of the bead-rolling test itself. Nevertheless, we emphasize that the degree of accuracy to predict PL using the new tool is still remarkably good. Therefore, the proposed device and the method are capable of predicting the two consistency limits employing the very same data, eliminating the second set of test devices and/or an operator.

The new approach is superior to the conventional methods in several aspects as follows:

1. It eliminates a number of uncertainties involved in the conventional tests of LL and PL.
2. Because it does not requires experience, the operator-dependency is no longer a matter of concern.
3. The most common two Atterberg limits can be determined using only one tool.
4. The test duration is remarkably short. All the data needed to find these two Atterberg limits are obtained in about 1 h, which is also shorter than the duration for determining Atterberg limits using the reverse extrusion test as described by Kayabali and Tufenkci (2010) and Kayabali (2012).
5. The device is simple and lightweight. It can be used anywhere in a laboratory.
6. The cost of manufacture is low as well. The most prominent components of the new tool are a loadcell and the display unit.

We propose that the newly proposed method be denoted as "Kayabali method."

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