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Determination of Atterberg Limits using the vane shear test method

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ABSTRACT

Atterberg limits are important index parameters used to classify soils for various engineering applications. Engineering properties of soils are predicted through simple correlations with index properties and thereby the engineering behavior of soils are qualitatively assessed. There are two popular methods of determining liquid limit, and plastic limit is commonly determined adopting rolling thread methods. To avoid operator related variations in determining plastic limit by conventional method, some researchers have explored using cone method as an alternative. However, there is no consensus about the depth of penetration to reckon the end of plastic state. Though various other test methods have been developed to determine plastic limit (like roll plate device), cone penetration with its limitation of determining plastic limit, is the only method to determine both liquid and plastic limit of soils. Since laboratory vane shear test is a simple and reliable method of determining undrained strength of fine-grained soils, the authors have explored to determine both liquid and plastic limits through correlations developed between undrained strength and water content over a range of consistencies between liquid and plastic states. This would eliminate determining liquid and plastic limit separately without sacrificing the reliability of results.

1. Introduction

Atterberg's original proposal for consistency limits (Atterberg, 1911) included seven qualitative limits, of which only two found more common usage in geotechnical engineering, namely liquid limit (LL) and plastic limit (PL). LL is the water content at which the soil starts to flow under its own weight. PL is the onset of soil brittleness or the water content corresponding to the transition from plastic- to semi-solid state.

The LL and PL, either individually or in the form of plasticity index (PI) have been used in a number of empirical correlations and can be helpful for preliminary estimates in the early stages of design. Such applications include classification of soils (Feng, 2004a), prediction of engineering properties like undrained shear strength (Skempton, 1954), consolidation parameters [e.g., the coefficient of compression, coefficient of recompression, preconsolidation pressure, settlement (Terzaghi and Peck, 1967; Azzouz et al., 1976; Leonards, 1976; Nagaraj and Srinivasa Murthy, 1986)], and determination of soil penetration resistance (Stroud, 1974) and the like.

The most common techniques to determine the liquid limit are the Casagrande cup and cone penetration test; and plastic limit are the thread rolling methods. Determination of LL by the Casagrande cup method involves a number of uncertainties (see, for instance, Wroth and Wood, 1978; Lee and Freeman, 2007; Kayabali and Tufenkci 2010a). The fall cone method is advantageous in comparison with Casagrande's method as it has less operator dependent variations

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and has good reproducibility of results. It also gives much lower standard deviation of the results than the cup test when identical samples are tested at multiple laboratories (Sherwood and Ryley, 1970; Haigh, 2012). Thus, there is not much debate on the uncertainties of fall cone tests. However, determination of plastic limit by the thread rolling method has always been a point of concern due to its operator related variations. Hence, a number of attempts have been made to determine the plastic limit using the fall cone method. Some of such attempts include the works of Towner (1973), Campbell (1976, 1983), Wood and Wroth (1978), Campbell et al. (1980), Feng (2000, 2001), Belviso et al. (1985), Rao (1987), Harison (1988), Sharma and Bora (2003), Feng (2004a, 2004b), Al-Dahlaki and Al-Sharify (2008), Rashid et al. (2008), Lee and Freeman (2009), Sivakumar et al. (2009), and Sivakumar et al. (2014). Shimobe (2010), using various types of cones, concluded that the "extended" fall cone method is capable of simultaneously determining both the liquid and plastic limits. He further stated that the fall cone test can also be used to determine the liquidity index as a state quantity, the undrained shear strength, and sensitivity of soils in terms of the cone penetration. Extrusion method was also employed as a tool to determine the consistency limits of fine-grained soils. Timar (1974), using the direct extrusion method, obtained partial success towards determining the two most common consistency limits. Whyte (1982), based on the results of preliminary reverse extrusion (RX) tests on a low plasticity clay, showed that RX is a reliable method for determining soil plasticity; also, that it is simple, rapid and economical. Kayabali and Tufenkci (2010b) showed that the RX test can provide a reasonable degree of success in determining LL and PL and that the RX test eliminates most of the uncertainties involved in both the conventional PL and LL tests, most importantly those that are operator dependent. Kayabali et al. (2016) developed a testing apparatus called the mud press machine (MPM). Using the test results of 275 soil samples, the authors of the study showed that Atterberg limits can be determined in a more rational and quantifiable basis using the MPM.

Vane shear test is one of the most common tools to assess the undrained shear strength of cohesive soils. It can be employed both in the laboratory and in the field. It was originated in Sweden in the early 1900s and became popular towards 1940s. Major advantages of the test are: ease to conduct, simplicity, robustness and speed. It also allows the measurement of peak and residual strength, and therefore, the sensitivity of cohesive soils. It provides an indirect assessment of over-consolidation ratio of a soil deposit as well (Ameratunga et al., 2016). It is recommended to be used on soils with an undrained shear strength less than 100 kPa (ASTM, 2000). The miniature vane test employing four springs with different stiffnesses is capable of measuring undrained shear strength of soils from a few kPa to about 100 kPa, which is the common range for the plastic behavior between the liquid and the plastic limit of fine-grained soils.

Kyambadde (2010) stated that, although VST is not the most attractive method, it provides a degree of validation of liquid limit data where vane shear strength relationships are available.

The scope of this investigation is to illustrate the usability of miniature vane shear test to determine the two major Atterberg limits.

2. Materials and Methods

One hundred soil samples were subjected to Atterberg limits and vane shear tests. Majority of the soil samples used in the study were residual soils produced by weathering of igneous rocks and few soils were lacustrine deposits obtained in the vicinity of Ankara, Türkiye. The soils selected to be used in this study were such that they had a wide range of plasticity. The liquid limits ranged from 23 to 106, and the plasticity index ranged from 7.5 to 50. The positions of soil samples on the plasticity chart are presented in Figure 1.

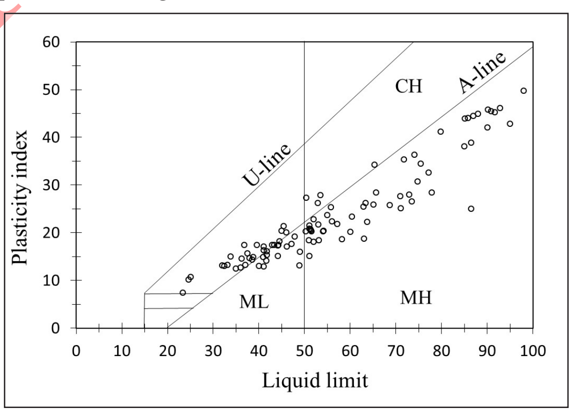

Figure 1- Positions of soil samples on the Casagrande chart.

The various equipment employed for this experimental research includes a fall-cone, a roll-plate device and a miniature vane shear apparatus which are respectively shown in Figure 2 to 4. The device for the vane shear test (Figure 4) measures the torque by electronic transducers instead of by springs. It facilitates measurement of torque up to 3.0 N.m. The measurable shear stress using this servo-controlled VST device ranges from 0.1-466 kPa when the blade dimensions are 12.7 mm x 12.7 mm. The rotational speed ranges from 0.001-1200 degrees per minute.

Figure 2- The fall cone device used in this investigation.

Figure 3- Roll-plate device for plastic limit tests.

All soil specimens were first sieved through an ASTM #40 mesh (American Society for Testing Materials, 2005). Then, sufficient quantity of water was added and the soil was mixed thoroughly before transferring into polythene covers. The mixed soil samples in polythene covers were properly labelled, and were placed in desiccator filled with water at the bottom to maintain 100% humidity. The samples were left for at least 20 h for proper saturation. For each of the soil samples the liquid limit was determined by using a fall-cone device (BS1377-1990). At least five trial points were obtained by varying the water content from dry side to wet side and the corresponding cone penetration was recorded. The range of cone penetration was targeted to be between 15 mm to 25 mm. Water content corresponding to 20 mm penetration was reckoned as the liquid limit of soil (British Standards Institution, 1990). Plastic limit of all the soils was evaluated as per the standard procedure outlined in ASTM D4318-05 Standard (American Society for Testing Materials, 2005) using the roll-plate device. Tests were repeated at least 5 times and the average of five plastic limit tests was taken to represent the soil subjected to the roll-plate test. The test results of liquid limit and plastic limit of all the soils are tabulated in Table 1.

Figure 4- Miniature vane shear test device.

The vane shear tests were performed in accordance with the ASTM D4648-00 Standard (American Society of Testing Materials, 2000). Each of the soils used in the study was prepared in a similar way as done for the liquid limit and plastic limit test. The test procedure involved conducting five trials of vane shear tests using the saturated soil having a consistency between the liquid limit and plastic limit.

Table 1- The results of Atterberg Limits tests and vane shear tests (LL: liquid limit, PL: plastic limit, PI: plasticity index, USCS: Unified Soil Classification System, a and b: coefficients obtained from the curve fitted to the semi-logarithmic experimental curve of the vane shear test, R^2: the regression coefficient, ML: silt of low plasticity silt, MH: silt of high plasticity, CL: clay of low plasticity, CH: clay of high plasticity).

No.	LL	PL	PI	USCS	a	b	R^2
1	51.1	35.9	15.2	MH	2E+08	0.377	0.976
2	63.0	44.2	18.8	MH	5.E+07	0.287	0.970
3	77.2	44.6	32.6	MH	14909	0.118	0.976
4	32.4	19.3	13.1	CL	12109	0.271	0.988
5	60.4	37.0	23.4	MH	5968	0.109	0.986
6	43.3	25.8	17.5	CL	44731	0.246	0.988
7	41.0	28.0	13.0	ML	163178	0.275	0.950
8	40.0	26.9	13.1	ML	211404	0.288	0.988
9	47.1	29.4	17.7	ML	21980	0.187	0.980
10	41.7	25.6	16.1	CL	63439	0.259	0.991
11	37.0	23.7	13.3	CL	8959	0.242	0.998
12	42.9	25.4	17.5	CL	17698	0.219	0.990
13	36.2	21.6	14.6	CL	16136	0.25	0.985
14	44.5	26.3	18.2	CL	31014	0.228	0.999
15	51.3	30.5	20.8	MH	8595	0.145	0.978
16	36.0	23.3	12.7	CL	24575	0.255	0.998
17	35.0	22.5	12.5	CL	32018	0.26	0.998
18	41.0	23.9	17.1	CL	96358	0.277	0.993
19	23.3	15.8	7.5	CL	26556	0.323	0.998
20	52.0	29.2	22.8	MH	16740	0.169	0.922
21	86.5	47.6	38.9	MH	6093	0.086	0.966
22	46.0	25.9	20.1	CL	7303	0.166	0.985
23	39.6	22.1	17.5	CL	14016	0.226	0.992
24	45.4	24.0	21.4	CL	6445	0.175	0.998
25	65.6	37.2	28.4	MH	171511	0.192	0.972
26	75.4	40.9	34.5	MH	8817	0.112	0.992
27	72.9	44.9	28.0	MH	5341	0.096	0.971
28	103	62.2	40.8	MH	7639	0.074	0.943
29	41.7	26.3	15.4	ML	22955	0.22	0.997
30	46.1	29.0	17.1	ML	83707	0.246	0.981
31	54.1	33.7	20.4	MH	20170	0.166	0.997
32	56.1	33.6	22.5	MH	88339	0.214	0.996
33	51.5	31.2	20.3	MH	25663	0.192	0.978

Table 1- Continue.

No.	LL	PL	PI	USCS	a	b	R^2
34	74.7	43.9	30.8	MH	916	0.058	0.915
35	45.0	24.6	20.4	CL	7024	0.174	0.996
36	68.6	42.8	25.8	MH	34188	0.135	0.967
37	58.2	39.5	18.7	MH	54624	0.163	0.995
38	60.0	39.8	20.2	MH	344266	0.205	0.983
39	50.4	23.1	27.3	CH	3019	0.149	0.990
40	51.0	30.1	20.9	MH	104103	0.214	0.967
41	95.0	52.1	42.9	MH	2731	0.073	0.996
42	85.0	46.9	38.1	MH	3649	0.084	0.989
43	73.5	46.9	26.6	MH	120860	0.154	0.970
44	71.1	46.0	25.1	MH	11807	0.116	0.990
45	77.8	49.4	28.4	MH	1.E+06	0.174	0.991
46	101	62.2	38.3	MH	922631	0.145	0.934
47	48.9	35.7	13.2	ML	1.E+06	0.263	0.998
48	36.8	19.3	17.5	CL	3165	0.191	0.992
49	33.8	18.8	15.0	CL	6551	0.233	0.992
50	32.0	18.8	13.2	CL	24462	0.311	0.996
51	65.3	31.0	34.3	CH	2761	0.116	0.997
52	57.2	35.4	21.8	MH	56743	0.186	0.976
53	41.6	27.4	14.2	ML	6773	0.165	0.997
54	49.0	33.0	16.0	ML	883887	0.259	0.997
55	44.1	26.8	17.3	ML	75389	0.235	0.993
56	53.5	25.6	27.9	CH	8660	0.171	0.981
57	33.1	19.8	13.3	CL	10956	0.26	0.997
58	38.7	23.8	14.9	CL	1979	0.159	0.999
59	37.5	21.8	15.7	CL	4517	0.208	0.997
60	53.0	31.3	21.7	MH	81326	0.211	0.994
61	54.0	33.7	20.3	MH	424	0.067	0.941
62	85.1	41.1	44.0	MH	10705	0.108	0.986
63	62.9	37.4	25.5	MH	35110	0.161	0.996
64	55.8	30.4	25.4	MH	24486	0.178	0.987
65	38.5	24.1	14.4	CL	1922	0.161	0.993
66	44.1	28.9	15.2	ML	62961	0.229	0.994

Table 1- Continue.

No.	LL	PL	PI	USCS	a	b	R^2
67	63.4	37.1	26.3	MH	9868	0.133	0.991
68	44.3	26.8	17.5	ML	45369	0.222	0.991
69	55.0	31.3	23.7	MH	14609	0.159	0.989
70	51.1	29.6	21.5	MH	18762	0.174	0.993
71	52.0	33.9	18.1	MH	2.E+06	0.275	0.987
72	41.0	24.6	16.4	CL	62589	0.261	0.996
73	37.9	23.2	14.7	CL	2567	0.178	0.995
74	65.1	39.2	25.9	MH	164541	0.184	0.986
75	50.2	29.9	20.3	MH	26825	0.194	0.984
76	63.7	41.4	22.3	MH	8.E+06	0.258	0.980
77	40.9	26.0	14.9	ML	136616	0.281	0.988
78	50.9	32.5	18.4	MH	36741	0.191	0.998
79	71.8	36.4	35.4	MH	283563	0.202	0.984
80	53.1	34.6	18.5	MH	853309	0.247	0.986
81	47.8	28.6	19.2	ML	18210	0.181	0.977
82	52.9	26.7	26.2	CH	5226	0.149	0.984
83	86.5	61.5	25.0	MH	174311	0.127	0.996
84	106	73.8	32.4	MH	49136	0.092	0.997
85	91.7	46.4	45.3	MH	1707	0.072	0.960
86	51.4	30.9	20.5	MH	9713	0.16	0.993
87	102	66.7	35.1	MH	39473	0.098	0.995
88	70.9	43.2	27.7	MH	4576	0.108	0.985
89	24.6	14.4	10.2	CL	9276	0.353	0.999
90	25.1	14.4	10.7	CL	4485	0.271	0.978
91	74.0	37.7	36.3	MH	2981	0.094	0.992
92	79.8	38.6	41.2	MH	4561	0.101	0.992
93	85.8	41.7	44.1	MH	2371	0.085	0.990
94	86.9	42.4	44.5	MH	5409	0.097	0.989
95	88.0	43.1	44.9	MH	3884	0.088	0.991
96	90.2	44.4	45.8	MH	2425	0.078	0.995
97	90.8	45.3	45.5	MH	4599	0.089	0.997
98	92.8	46.7	46.1	MH	2475	0.075	0.996
99	90.0	47.9	42.1	MH	4725	0.084	0.990
100	98.0	48.2	49.8	MH	1905	0.067	0.993

The measured torques were converted to undrained shear strengths using the relationships given in equations (1) and (2) (American Society of Testing Materials, 2000):

$$T = \tau \times K \qquad (1)$$

$$K = \frac{\pi D^2}{2x10^6}\left[1 + \frac{D}{3H}\right] \qquad (2)$$

where T = torque (N.m), τ = undrained shear strength (N/m^2), K = vane blade constant (m^3), D = measured diameter of the vane (mm) and H = measured height of the vane (mm). The measured undrained shear strengths with respective water contents were plotted in a semi-logarithmic plot. One such typical plot for soil No. 58 is shown in Figure 5, from which an equation was obtained in the following form:

$$y = a \exp^{b} \qquad (3)$$

where y is the undrained shear strength (su) and a and b are the regression coefficients.

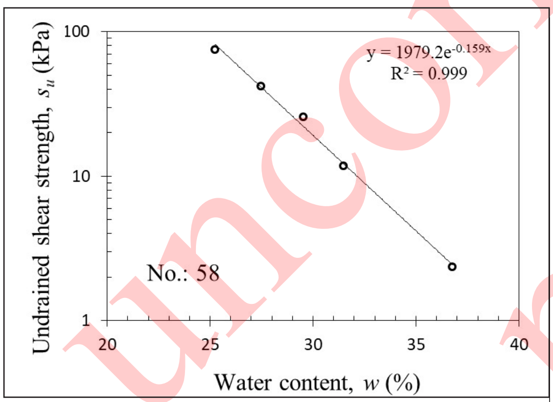

Figure 5- A sample plot constructed upon VST test results.

3. Experimental Results

From Table 1, it can be seen that of the 100 samples collected from different locations, 57 soils are classified as MH (silt of high plasticity), 26 are classified as CL (clay of low plasticity), 13 as ML (silt of low plasticity) and 4 as CH (clay of high plasticity). Thus, the soils covered a wide range of plasticities. As mentioned earlier, each soil sample was subjected to five vane shear tests at different water contents. Thus, the resulting number of undrained shear strength and water content pairs is 500 for 100 soil samples. Listing of such a large data occupies a great deal of space; so, to save space, the results of vane shear tests are presented only in terms of a and b coefficients as presented in Table 1.

In order to explore for a possible correlation between undrained shear strengths obtained from the miniature vane shear test and Atterberg limits, the numerical data presented in Table 1 was subjected to a series of statistical analyses. To show if it was possible to determine the liquid limit in terms of the undrained shear strength and water content, a multiple regression analysis was performed using the software DATAFIT (DATAFIT, 2008). This way a series of both complex and rather simple empirical equations were obtained defining the LL in terms of s_u and w. One of the simplest of such relationships are selected and provided as follows:

$$LL = 0.902\,(w^{0.997})\,s_u^{0.138} \qquad (R^2 = 0.92) \qquad (4)$$

where s_u is in kPa and w is in %. The maximum coefficient of correlation was 0.95 for highly complex polynomial equations which involved many constants. As a next step, Equation (4) was employed to predict the liquid limit empirically. Figure 6 is a plot of the empirically-predicted liquid limits with those determined experimentally using the fall-cone method. The deviations from the measured liquid limits were evaluated statistically in terms of absolute percent errors. Figure 7 is the histogram of absolute percent errors of the measured liquid limits when determining the liquid limit using the predictive Equation (4). The overall absolute percent error is 6.8%. A quick glimpse on Figure 7 reveals that the amount of error for the predicted liquid limits of 80% of all soils is within ±10%.

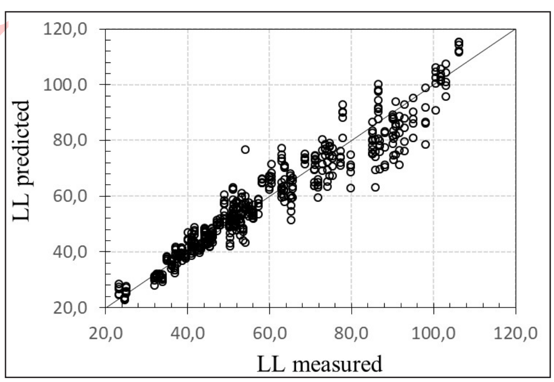

Figure 6- Comparison between the predicted liquid limits versus the measured liquid limits.

Similarly, 500 sets of water content, undrained shear strength and plastic limit were also subjected to a multiple regression analysis to predict the plastic limit in terms of water content and undrained shear strength. The following simple version of the empirical equation was obtained:

$$PL = 0.609\,(w^{0.959})\,s_u^{0.139} \qquad (R^2 = 0.95) \qquad (5)$$

In the next step, Equation (5) was employed to predict the plastic limit empirically. Figure 8 is a plot of the empirically-predicted plastic limits with those determined experimentally using the roll-plate method. The deviations from the measured plastic limits were evaluated statistically in terms of absolute percent errors. Figure 9 is the histogram of absolute percent errors of the measured plastic limits when determining the plastic limit using the predictive Equation 5. The overall absolute percent error is 5.3%. A quick glimpse on Figure 9 reveals that the amount of error for the predicted plastic limits of 86% of all soils is within ±10%.

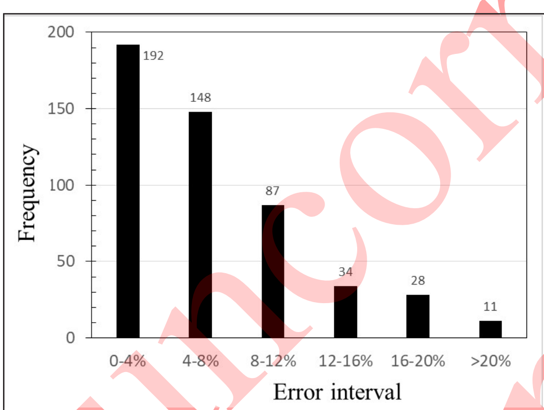

Figure 7- Histogram of absolute errors of predicted liquid limits.

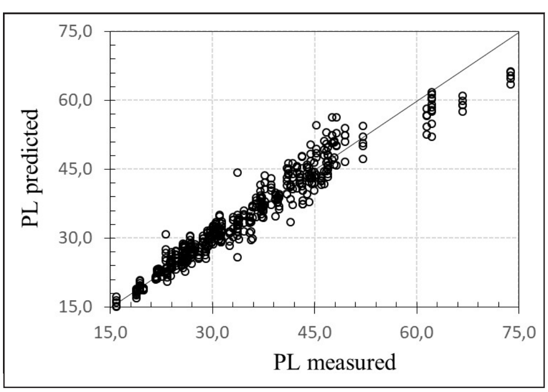

Figure 8- Comparison between the predicted plastic limits versus the measured plastic limits.

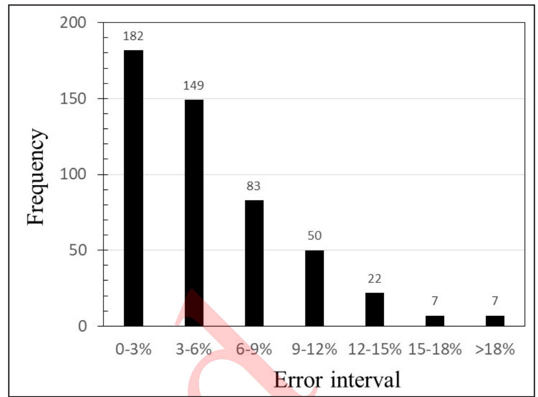

Figure 9- Histogram of absolute errors of predicted plastic limits.

Equation (4) and (5) are found very useful in that they can be used to predict the two Atterberg limits, namely the liquid limit and plastic limit based on a "single trial" of VST test which is done at any water content between plastic limit and liquid limit. To avoid error introduced by a single trial of VST test in predicting liquid and plastic limits, it is better to use the results of at least a few trials of vane shear tests conducted at different water contents between PL and LL, so that the coefficients 'a' and 'b' are obtained.

The coefficients 'a' and 'b' as presented in Table 1 for each soil sample were also subjected to multiple regression analyses along with the Atterberg limits data. One hundred sets of 'a' and 'b' coefficients and the liquid limit yield the following "short" version of the predictive equations:

$$LL = 3.62\,(a^{0.106})\,b^{-0.92} \qquad (R^2 = 0.92) \qquad (6)$$

Similarly, plastic limit is defined in terms of 'a' and 'b' coefficients:

$$PL = 1.72\,(a^{0.129})\,b^{-0.91} \qquad (R^2 = 0.92) \qquad (7)$$

The overall absolute percent error between the measured and predicted the liquid limits is 6.3% and that for plastic limit, it is 3.9%, which implies that the Atterberg limits are predicted with a slightly higher degree of accuracy than those predicted by Equations (4) and (5) which make use of water content and undrained shear strength.

4. Conclusions

In order to eliminate determining the liquid and plastic limit separately without sacrificing the reliability of estimating these limiting water contents, the authors have explored to determine both these limits using a laboratory vane shear test through the correlations developed between the undrained strength and water content over a range of consistency between the liquid and plastic states. From the vane test results of 100 natural soils used in this study having a wide range of plasticity properties, attempts to do a multi regression analysis of the two empirical coefficients 'a' and 'b' (obtained from the undrained strength versus water content of individual soils) with the LL and PL led to two separate correlation equations to empirically predict the LL and PL with the undrained strength and water content in terms of the empirical coefficients. Even a single test data from vane shear test at a water content between LL and PL can be just sufficient to predict LL and PL respectively using the correlation Equation 4 and 5. However, to improve the efficiency of predicting LL and PL, one can use the results of at least a few trials of vane shear tests conducted at different water contents between PL and LL, so that, the coefficients 'a' and 'b' are obtained. These coefficients can be used to predict LL and PL respectively using the correlation Equation 6 and 7. The developed correlations becomes handy to have an independent and quick check on the test results of LL and PL while handling large data generated at soil laboratories.

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