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Relationship between measured plastic limit and plastic limit estimated from undrained shear strength, water content ratio and liquidity index

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ABSTRACT: The detection of the plastic limit of clays is subject to human error. Several attempts have been made to correlate across studies the geotechnical properties of fine-grained soils (water content, liquidity index, shear strength, *etc.*). Based on the premise that the liquidity index and water content ratio can be correlated directly, an alternative method to obtain indirectly the plastic limit is suggested here. The present study investigated 40 natural clayey samples of various mineralogies and origins and other publicly available data, where Atterberg limits and undrained shear strength values obtained with the vane shear tests were given. The liquidity index and water-content ratio correlate very well for defined undrained shear strength values of the clays. Solving the liquidity index equation for the plastic limit, estimated plastic limit values obtained by the liquidity index/water-content ratio relationship were compared with laboratory plastic-limit values. Preliminary results based on 62 values show an exponential trend with a multiple regression coefficient of 0.79. The data need to be confirmed on a larger database, however.

KEYWORDS: water-content ratio, liquidity index, Atterberg limits, undrained shear strength.

The plastic limit (PL) of clays is determined by the rolling test and is defined as the smallest water content (expressed in mass% of the dried clay) where the soil mass begins to crumble when rolled into a thread of ~3 mm (*e.g.* Atterberg, 1911; Casagrande, 1932; Carter & Bentley, 1991; Bergaya *et al.*, 2006). The PL determination in geotechnical engineering is described in some of the main standards, *e.g.* BS 1377 (BSI, 1990), DIN 18122-1 (DIN, 1997), ASTM D4318 (ASTM, 2017).

According to Haigh *et al.* (2013), there is no fixed shear strength at PL or at liquid limit (LL) as reported by Casagrande (1932), Skempton & Northey (1953), Norman (1958) and Skopek & Ter-stepanian (1975), to name but a few. During the rolling test, the soil is remoulded continually and hence its stress state lies on the critical state line. The strength increases linearly with increasing pore suction (Haigh *et al.* 2013). Baker & Frydman (2009) suggested a range of undrained shear strength values, c_u, at PL of 65–400 kPa.

The determination of PL by the rolling method is prone to human error (Ballard & Weeks, 1963) from incorrect judgment on the part of the operator (Feng, 2004) due to incorrect measurement of diameter, or because the rolling process is stopped too soon (Andrade *et al.*, 2011). Therefore, the rolling thread method for determining PL may not provide a unique strength index (Nagaraj *et al.*, 2012). Several attempts

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have been made to determine PL using the cone penetrometer (*e.g.* Towner, 1973; Campbell, 1976; Belviso *et al.*, 1985; Wasti & Bezirci, 1986; Harrison, 1988; Stone & Phan, 1995) or using the extrusion method (*e.g.* Whyte, 1982) but no unequivocal outcome was reached (Nagaraj *et al.*, 2012).

A possible alternative solution might be to obtain the PL indirectly from a correlation linking the water content ratio (WCR), the liquidity index (LI) and the corresponding undrained shear strength value, c_u. The WCR is the ratio of water content to LL as defined by Kuriakose *et al.* (2017) and it is claimed to be an adequate replacement of the well known LI in terms of predicting the shear strength of fine-grained soils (see Kuriakose *et al.*, 2017).

$$\mathrm{LI} = \frac{w - \mathrm{PL}}{\mathrm{PI}} \quad (1)$$

where w is the water content, PL is the plastic limit and PI is the plasticity index.

The LI is used for scaling the natural water content, w, of a fine-grained soil sample to the limits LL and PL. Its value is 0 at PL and 1 at LL. Negative LI values indicate that the soil is drier than at PL, whereas LI values of >1 mean the soil is more liquid than at LL. Kuriakose *et al.* (2017) stated that WCR can be used instead of LI as an excellent linear relationship exists between LI and WCR.

The present study compared PL values obtained using the rolling test with calculated PL values obtained using estimates of WCR, LI and c_u. Many geotechnical properties of fine-grained soils can be inter-correlated, *e.g.* CEC with soil index properties (Yukselen & Kaya 2006), LI with clay sensitivity (Bjerrum, 1954) and undrained shear strength with water content (Berilgen *et al.* 2007), to name but a few. The undrained shear strength of clayey soils can be correlated with other geotechnical parameters, such as WCR (*e.g.* Federico, 1983a) and LI (Skempton & Northey, 1953; Schofield & Wroth, 1968; Whyte, 1982; Locat & Demers, 1988; Koumoto & Houlsby, 2001; Berilgen *et al.*, 2007). An exponential correlation with a multiple regression coefficient of 0.79 was obtained. A larger database must be analysed to confirm this behaviour, however.

MATERIALS AND METHODS

In order to conduct a preliminary investigation into the possibility of obtaining PL indirectly, 40 natural clayey samples with varying mineralogies obtained from various sites were tested (Table 1). The database was enlarged with data available from the literature, where Atterberg limits and undrained shear-strength values were determined using vane shear tests (*i.e.* Ola, 1978; Egashira & Ohtsubo, 1982; Touiti *et al.*, 2009; Strozyk & Tankiewicz, 2013; Kuriakose *et al.*, 2017). In total, 72 data sets were used.

In the present investigation (lines 1–40 in Table 1), Atterberg limits were determined according to the German standards DIN 18121 (2012) and DIN 18122 (1997), whereas vane shear tests according to DIN 4094-4 (2002) were used to determine the shear strength. The paste was made by mixing the clay with water and then kept in a closed bucket for 48 h to attain equilibrium. The water content was then measured to determine the consistency value. After that, the clay specimens (diameter = 100 mm, height = 120 mm) were compacted in a standard Proctor test (DIN 18127 2012) with an average compaction energy of 0.6 MNm/m^3. For the undrained shear tests the vane was inserted for 3 cm and a torque with a velocity of 2 cm/s was applied until the specimen failed.

The mineralogy of each of the clays 1–40 in Table 1 was obtained by means of X-ray diffraction (XRD) with a Bruker AXS D8-Advance diffractometer using Cu-$K\alpha$ radiation. The XRD data were collected between 2 and 92°2θ and measurements were made using a scanning step of 0.02°2θ and a fixed time of 3 s per step.

Regarding the literature research, not many data were found where lab vane test results were given along with Atterberg limits. With regard to the data of Egashira & Ohtsubo (1982), c_u values obtained from uniaxial tests (UCS) are also shown. These were not used for interpreting the data, however, but merely to highlight the different behaviours shown with respect to the correlation with LI and WCR.

RESULTS AND DISCUSSION

A relationship between vane shear strength and water content for (ultra-soft) clayey soils was shown to be valid by Yosuke *et al.* (2004). The Atterberg limits and shear strength depend on the clay mineralogy (Mitchell & Soga, 2005) and their influence is incorporated by normalizing the water content by expressing it as a ratio of LL, *i.e.* in WCR (Kuriakose *et al.*, 2017). The shear strength and WCR values shown in Table 1 have been plotted in Fig. 1.

The c_u values decrease with increasing WCR values up to 1. It is possible, in fact, to recognize how the c_u *vs.* WCR relation changes for WCR values of >1. The

TABLE 1. Summary of the Atterberg limits and vane shear-test results for the present study.

Sequence	Sample name	LL (%)	PL (%)	PI (%)	c_u (kPa)	w (%)	LI	WCR	Main clay mineralogy	Source
1	KBT Heading West	45.6	20	25.6	28.1	27.6	0.30	0.61	Not measured	Lab test
2	Garzweiler Open Pit Mine	59.3	20.9	38.4	9.17	38.2	0.45	0.64	Smectite (17.5%), Kaolinite (19%), Illite (42%)	Lab test
3	Sedan Pit	52.7	22.6	30.1	5.84	40.7	0.60	0.77	Illite (24%), Kaolinite (30%)	Lab test
4	Sedan Pit (bagged)	45.3	19.9	25.4	8.7	31.3	0.45	0.69	Kaolinite (50%), Illite (17%)	Lab test
5	Ypresian Clay	142.5	32.3	110.2	65.5	48.8	0.15	0.34	Smectite (44%), Illite (16%)	Lab test
6	Boom Clay	72.3	21.6	50.7	46.5	36.8	0.30	0.51	Smectite (24%), Kaolinite (10%), Illite (15%)	Lab test
7	U4 HH Cross Cut	52.7	18.3	34.4	6	52	0.98	0.99	Smectite (15%), Kaolinite (6%), Illite (11%)	Lab test
8	KBT Meletta Mixed Sample	51.5	18	33.5	29.8	28.5	0.31	0.55	Smectite (22%), Kaolinite (3%), Illite (14%)	Lab test
9	KBT North Portal	30.7	18.5	12.2	11.4	23.9	0.45	0.78	Kaolinite (5%), Illite (13%)	Lab test
10	KBT South Portal	40.6	22.3	18.3	19.5	27.7	0.30	0.68	Smectite (18%), Kaolinite (4%), Illite (11%)	Lab test
11	Warsaw Clay	66.5	19.8	46.7	45.4	26.8	0.15	0.40	Smectite (35%), Kaolinite (3%), Illite (7%)	Lab test
12	Frankfurt Clay	72.5	25.5	47	29.8	39.6	0.30	0.55	Smectite (54%), Kaolinite (2%), Illite (2%)	Lab test
13	Wimpfsfeld II Pit	41.0	16.6	24.4	51.9	20.2	0.15	0.49	Kaolinite (48%), Illite (15%)	Lab test
14	Rome Clay	42.5	21.1	21.4	38.41	27.5	0.30	0.65	Illite (9%)	Lab test
15	London Clay	74.0	20.6	53.4	33.54	36.6	0.30	0.49	Smectite (35%), Kaolinite (25%), Illite (21%)	Lab test
16	KBT Cross Cut 12	24.6	12.2	12.4	14.61	15.9	0.30	0.65	Smectite (12%), Kaolinite (7%), Illite (12%)	Lab test
17	Aresing Clay	46.5	15.5	31	11.9	34.1	0.60	0.73	Smectite (16%), Illite (28%)	Lab test
18	Kaolinite	60.9	35.6	25.3	25.4	39.3	0.15	0.65	Kaolinite (80%)	Lab test
19	Illite	57.5	38.6	18.9	29.75	49.9	0.60	0.87	Illite (95%)	Lab test
20	Emscher Mergel I	53.8	22.9	30.9	37.3	27.5	0.15	0.51	Smectite (14%), Kaolinite (3%), Illite (22%)	Lab test
21	Emscher Mergel II	38.2	20.9	17.3	29.75	23.5	0.15	0.62	Not measured	Lab test
22	Emscher Mergel III	51.9	17.4	34.5	19.47	32.9	0.45	0.63	Smectite (27%), Kaolinite (4%), Illite (8%)	Lab test

(continued)

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TABLE 1. (*contd.*)

Sequence	Sample name	LL (%)	PL (%)	PI (%)	c_u (kPa)	w (%)	LI	WCR	Main clay mineralogy	Source
23	Emscher Mergel IV	50.7	26.3	24.4	22.18	33.6	0.30	0.66	Smectite (28%), Kaolinite (5%), Illite (8%)	Lab test
24	Emscher Mergel V	51.4	20.5	30.9	8.66	39	0.60	0.76	Smectite (14%), Kaolinite (3%), Illite (22%)	Lab test
25	Emscher Mergel VI	52.2	17.4	34.8	29.21	27.8	0.30	0.53	Smectite (24%), Kaolinite (5%), Illite (9%)	Lab test
26	Emscher Mergel VII	41.6	19.1	22.5	30.84	29.2	0.45	0.70	Smectite (28%), Illite (6%)	Lab test
27	Emscher Mergel VIII	38.2	20.9	17.3	26.51	26.09	0.30	0.68	Not measured	Lab test
28	Project NN Clay I Sample I	37.8	19.8	18.1	45.95	25.22	0.30	0.67	Smectite (11%), Kaolinite (2%), Illite (13%)	Lab test
29	Project NN Clay I Sample II	50.2	22.3	27.9	8.86	44.6	0.80	0.89	Smectite (20%), Kaolinite (5%), Illite (9%)	Lab test
30	Project NN Clay I Sample III	43.4	22.8	20.7	9.97	35.2	0.60	0.81	Smectite (23%), Kaolinite (5%), Illite (9%)	Lab test
31	Project NN Clay I Sample IV	50.0	24	26	8.11	35.7	0.45	0.71	Smectite (12%), Kaolinite (7%), Illite (19%)	Lab test
32	Project NN Clay I Sample V	45.1	21.9	23.2	38.21	28.8	0.30	0.64	Smectite (18%), Kaolinite (6%), Illite (15%)	Lab test
33	Project NN Clay I Sample VI	54.1	25.02	29.14	3.32	48.3	0.80	0.89	Smectite (18%), Kaolinite (6%), Illite (8%)	Lab test
34	Project NN Clay I Sample VII	49.9	25.9	24	8.86	40.3	0.60	0.81	Smectite (21%), Kaolinite (7%), Illite (9%)	Lab test
35	Project NN Clay I Sample VIII	47.2	25.8	21.4	24.37	35.4	0.45	0.75	Smectite (24%), Kaolinite (8%), Illite (11%)	Lab test
36	Project NN Clay I Sample IX	43.3	26.2	17.1	22.15	31.3	0.30	0.72	Smectite (19%), Kaolinite (7%), Illite (9%)	Lab test
37	Project NN Clay I Sample X	48.7	25.9	22.8	3.79	44.1	0.80	0.91	Smectite (24%), Kaolinite (5%), Illite (8%)	Lab test
38	Project NN Clay I Sample XI	51.3	23	28.3	16.77	40.0	0.60	0.78	Smectite (17%), Kaolinite (4%), Illite (16%)	Lab test
39	Project NN Clay I Sample XII	49.7	23.2	26.5	10.52	35.1	0.45	0.71	Smectite (21%), Kaolinite (7%), Illite (10%)	Lab test
40	Project NN Clay I Sample XIII	50.1	20.4	29.7	24.92	29.3	0.30	0.59	Smectite (20%), Kaolinite (4%), Illite (9%)	Lab test

(*continued*)

TABLE 1. (*contd.*)

Sequence	Sample name	LL (%)	PL (%)	PI (%)	c_u (kPa)	w (%)	LI	WCR	Main clay mineralogy	Source
41	1	78.0	31	47	120	27.0	–0.09	0.35	Montmorillonite/kaolinite	Ola (1978)
42	1	105.0	42	63	9.8	126.0	1.33	1.20	Smectite (33–42%)	Egashira & Ohtsubo (1982)
43	2	46.0	34	12	13.8	68.0	2.83	1.48	Smectite (33–42%)	Egashira & Ohtsubo (1982)
44	3[a]	72.0	35	37	15.3	79.0	1.19	1.10	Smectite (33–42%)	Egashira & Ohtsubo (1982)
45	4[a]	61.0	30	31	25.1	88.0	1.87	1.44	Smectite (33–42%)	Egashira & Ohtsubo (1982)
46	5[a]	68.0	40	28	13.2	96.0	2.00	1.41	Smectite (33–42%)	Egashira & Ohtsubo (1982)
47	6[a]	63.0	33	30	40.9	93.0	2.00	1.48	Smectite (33–42%)	Egashira & Ohtsubo (1982)
48	7[a]	54.0	31	23	26.1	87.0	2.43	1.61	Smectite (33–42%)	Egashira & Ohtsubo (1982)
49	8[a]	149.0	53	96	12.7	157.0	1.08	1.05	Smectite (33–42%)	Egashira & Ohtsubo (1982)
50	9[a]	114.0	51	63	14.2	127.0	1.21	1.11	Smectite (33–42%)	Egashira & Ohtsubo (1982)
51	1	65.0	35	30	20	81.0	1.53	1.25	Not mentioned	Touiti *et al.* (2009)
52	2	65.0	33	32	17	51.0	0.56	0.78	Not mentioned	Touiti *et al.* (2009)
53	3	55.0	28	27	17	51.0	0.85	0.93	Not mentioned	Touiti *et al.* (2009)
54	1	96.2	26.5	69.7	96.7	22.9	–0.05	0.24	Not mentioned	Strozyk & Tankiewicz (2013)
55	2	38.4	16.4	22	59.2	17.1	0.03	0.45	Not mentioned	Strozyk & Tankiewicz (2013)
56	3	61.5	24.4	37.1	99.5	18.7	–0.15	0.30	Not mentioned	Strozyk & Tankiewicz (2013)
57	4	59.2	26.4	32.8	92.6	24.4	–0.06	0.41	Not mentioned	Strozyk & Tankiewicz (2013)
58	5	57.3	21.3	36	32.3	22.2	0.03	0.39	Not mentioned	Strozyk & Tankiewicz (2013)
59	6	43.0	22.1	20.9	55.6	24.4	0.11	0.57	Not mentioned	Strozyk & Tankiewicz (2013)
60	7	66.5	24.4	42.1	139	24.3	0.00	0.37	Not mentioned	Strozyk & Tankiewicz (2013)
61	8	68.1	27.6	40.5	100.4	22.2	–0.13	0.33	Not mentioned	Strozyk & Tankiewicz (2013)
62	9	51.2	20.3	30.9	111.5	20.0	–0.01	0.39	Not mentioned	Strozyk & Tankiewicz (2013)
63	10	83.8	27.7	56.1	169.1	20.0	–0.14	0.24	Not mentioned	Strozyk & Tankiewicz (2013)
64	11	91.3	29.1	62.2	149	28.2	–0.01	0.31	Not mentioned	Strozyk & Tankiewicz (2013)
65	12	64.1	27	37.1	133.3	19.9	–0.19	0.31	Not mentioned	Strozyk & Tankiewicz (2013)

(continued)

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TABLE 1. (*contd.*)

Sequence	Sample name	LL (%)	PL (%)	PI (%)	c_u (kPa)	w (%)	LI	WCR	Main clay mineralogy	Source
66	13	55.6	23.5	32.1	139.2	22.6	–0.03	0.41	Not mentioned	Strozyk & Tankiewicz (2013)
67	14	67.6	22	45.6	109.4	22.5	0.01	0.33	Not mentioned	Strozyk & Tankiewicz (2013)
68	15	59.7	26.3	33.4	177.7	22.4	–0.12	0.38	Not mentioned	Strozyk & Tankiewicz (2013)
69	1	108.0	43	65	2.1	105.6	0.96	0.98	Kaolinite (8%), Illite (19%), Chlorite (26%)[b]	Kuriakose *et al.* (2017)
70	2	105.0	45	60	1.75	105.0	1.00	1.00	Kaolinite (8%), Illite (19%), Chlorite (26%)[b]	Kuriakose *et al.* (2017)
71	3	119.0	47	72	2.36	105.8	0.82	0.89	Kaolinite (8%), Illite (19%), Chlorite (26%)[b]	Kuriakose *et al.* (2017)
72	4	98.0	39	59	1.9	98.0	1.00	1.00	Kaolinite (8%), Illite (19%), Chlorite (26%)[b]	Kuriakose *et al.* (2017)

[a]The c_u values of Egashira & Ohtsubo (1982) were obtained from the unconfined compressive strength and were not utilized in obtaining the correlations shown in Figs 1–4.
[b]Clay mineralogy reported by Rajasekaran *et al.* (1994).

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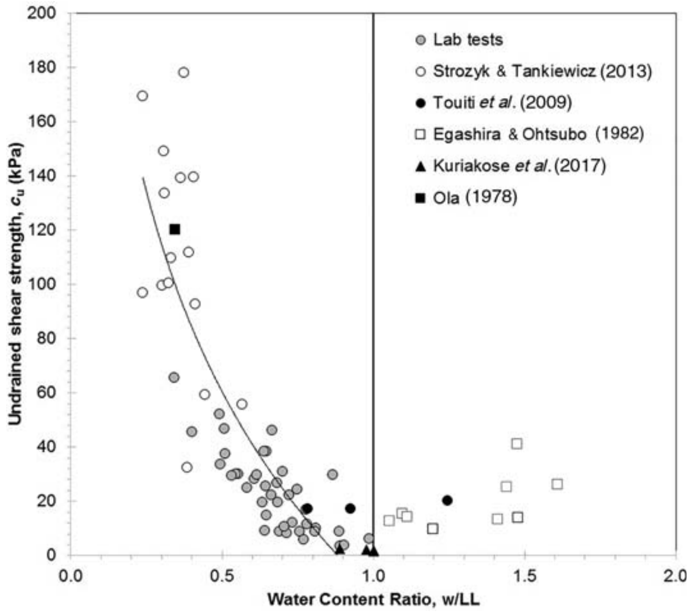

FIG. 1. Undrained shear strength *vs*. WCR for the data shown in Table 1. The open grey squares refer to the laboratory data of Egashira & Ohtsubo (1982) where c_u was obtained by means of UCS tests. It is possible to recognize a change in behaviour for WCR > 1.

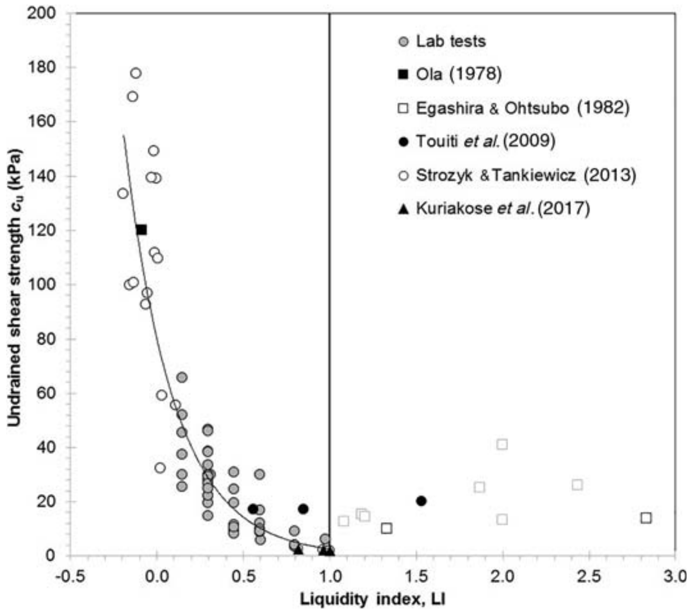

FIG. 2. Undrained shear strength *vs*. LI for the data shown in Table 1. The open grey squares refer to the laboratory data of Egashira & Ohtsubo (1982) where c_u was obtained by means of UCS tests. It is possible to recognize a change in behaviour for LI > 1.

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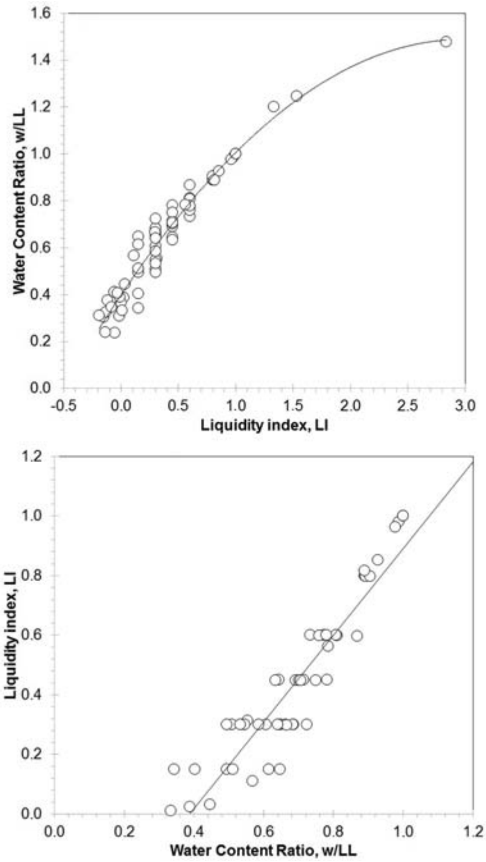

FIG. 3. WCR *vs*. LI correlation (a) and LI *vs*. WCR correlation (b). Note that in Fig. 3a all the values of WCR and LI are considered (except for those where c_u values are from UCS tests), whereas in Fig. 3b only values of WCR and LI up to a value of 1 are taken into consideration.

open grey squares refer to the lab data of Egashira & Ohtsubo (1982) where c_u was obtained by UCS tests. These data were displayed to show the behaviour for WCR values of >1.

The data plotted on the left side of the graph are interpolated by an exponential function with a good coefficient of determination, $R^2 = 0.82$. The exponential function with the form:

$$c_u = 597.82e^{-5.131\text{WCR}} \quad (2)$$

is in the range w = (0.24 to 1.61)LL. The exponential function has also been confirmed by Federico (1983a,b).

As mentioned above, c_u has also been correlated to LI by several authors (see Nagaraj *et al*. 2012 for a summary of the various relations found). For the database compiled for this research, a c_u/LI relationship is shown in Fig. 2. Similar to Fig. 1 the data plotted on the left side of the graph are interpolated by an exponential function with a good coefficient of determination, $R^2 = 0.85$. Also, similar to the c_u/WCR graph, the data on the right side of the graph (*i.e.* values >1) show an inverted trend, although less well expressed. It seems that the relationship is not valid for water contents greater than the LL.

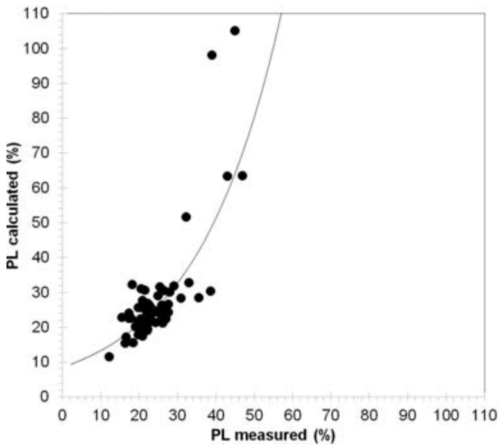

FIG. 4. Relationship between $PL_{calculated}$ and $PL_{measured}$.

The results in Figs 1 and 2 confirm the findings of Kuriakose *et al*. (2017) who pointed out the advantages of using WCR rather than LI for predicting the undrained shear behaviour of a fine-grained soil.

Figure 3 shows the WCR *vs*. LI correlation (a) and *vice versa* (b). Data in Fig. 3a are interpolated by a polynomial function, while data in Fig. 3b are interpolated by a linear regression function, both with high coefficients of determination (0.94 for Fig. 3a and 0.91 for Fig. 3b).

Also, in Fig. 3a all the data from Table 1, except for the c_u values obtained using UCS tests, were taken into account; in Fig. 3b, only the values of LI and WCR up to a value of 1 are listed.

Considering the linear function of Fig. 3b, which is in the form:

$$\text{LI} = 1.45\text{WCR} - 0.56 \quad (3)$$

the estimated LI value is obtained.

Solving equation 1 for PL, the estimated value was compared with the laboratory PL values listed in Table 1 and the comparison is shown in Fig. 4 in which the correlation 'calculated PL *vs.* measured PL' is

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TABLE 2. Statistical data for the correlation LI *vs*. WCR of Fig. 3b.

Multiple R	R^2	Adjusted R^2	Standard error	No. of samples	*p* value
0.95	0.91	0.91	0.01	62	3.92×10^{-33}

TABLE 3. Statistical data for the correlation $PL_{calculated}$ *vs*. $PL_{measured}$ in Fig. 4.

Multiple R	R^2	Adjusted R^2	Standard error	No. of samples	*p* value
0.79	0.62	0.62	11.3	62	2.85×10^{-14}

exponential with a multiple regression coefficient of 0.79, in the form:

$$PL_{calculated(\%)} = 7.42 \cdot e^{0.05 \cdot PL_{measured(\%)}} \quad (4)$$

The calculated PL tends to overestimate the measured PL over the range of PL investigated for the research (12–53%). Those calculated PL values which overestimate the PL measured to a considerable extent are those with the natural water content of >90% (parameter needed to estimate the LI).

Considering that 62 of the 72 data were used to obtain this correlation (the LI or WCR values >1 and the UCS c_u values of Egashira & Ohtsubo (1982) were not considered), there is a significant positive relationship between LI and WCR with r(62) = 0.95 with *p* value <0.05 (*i.e.* 3.92×10^{-33}), leading to Fig. 4. Besides, the multiple regression coefficient of Fig. 4 is 0.79 also with a very small *p* value, namely 2.85×10^{-14}, again confirming the statistical significance of the correlation.

The statistical data illustrated in Figs 3b, 4 are listed in Tables 2 and 3. The data shown in Fig. 4 were also interpreted by considering the main mineralogy, where given, to find out whether the main clay minerals present may explain the results, but no particular trend was found.

Despite the relatively small number of data used in the present study, an indirect evaluation of the PL from other geotechnical data seems possible. Further steps require the creation of a larger database to confirm this trend.

SUMMARY AND CONCLUSIONS

Plastic limit (PL) values determined using the Casagrande method are prone to human error. As Atterberg limits have been correlated to the water content ratio (WCR) and liquidity index (LI), an alternative approach was proposed to estimate indirectly PL from WCR and LI considering the undrained shear strength, c_u. Forty Atterberg limit values and vane shear tests on various clayey soils were performed. The database was enlarged by adding other, publicly available data from the literature. The undrained shear strength/water content ratio (or liquidity index) relationships were exponential with high coefficients of determination (R^2 = 0.82–0.85). This relationship is only valid for WCR (or LI) values up to 1. For higher values the trend is reversed, *i.e.* for increasing WCR (or LI) values, c_u values increase.

Considering the similarities between c_u *vs.* WCR and c_u *vs.* LI, WCR and LI plots were created. Both relationships are interpolated with extremely good R^2 values (0.94 and 0.91). Besides, the LI/WCR relationship showed good statistical significance with *p* values <0.001. Solving the LI equation for PL, the estimated value was compared to the laboratory PL values. The relationship between the calculated PL and the measured PL gave a good statistical significance with *p* value <0.001 and a multiple regression coefficient of 0.79. Results based on 62 data suggest a possible estimation of PL based on the LI, WCR and c_u assessment. However, extension of the database is recommended in order to confirm this trend.

REFERENCES

Andrade F.A., Al-Qureshi H.A. & Hotza D. (2011) Measuring the plasticity of clays: A review. *Applied Clay Science*, **51**, 1–7.

ASTM D4318 (2017) *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. ASTM International, West Conshohocken, Pennsylvania, USA.

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Atterberg A. (1911) Die Plastizität der Tone. *Mitteilungen für Bodenkunde*, **1**, 10–43 (in German).
Baker R. & Frydman S. (2009) Unsaturated soil mechanics: critical review of physical foundations. *Engineering Geology*, **106**, 26–33.
Ballard G.E.H. & Weeks W.F. (1963) Human error in determining plastic limit of cohesive soils. *Materials Research and Standards*, **3**, 726–729.
Belviso R., Ciampoli S., Cotecchia V. & Federico A. (1985) Use of the cone penetrometer to determine consistency limits. *Ground Engineering*, **18**, 21–22.
Bergaya F., Theng B.K.G. & Lagaly G. (2006) *Handbook of Clay Science*. Elsevier, Amsterdam.
Berilgen S.A., Kilic H. & Özaydın K. (2007) Determination of undrained shear strength for dredged golden horn marine clay with laboratory tests. *Proceedings of the Sri Lankan Geotechnical Society's first international conference on soil & rock engineering*, August 5–11, Colombo, Sri Lanka.
Bjerrum L. (1954) Geotechnical properties of Norwegian marine clays. *Geotechnique*, **4**, 49–69.
BSI (1990) Methods of test for soils for civil engineering purposes. BS 1377. British Standards Institution, Milton Keynes, UK.
Campbell D.J. (1976) Plastic limit determination using a drop cone penetrometer. *Soil Science*, **27**, 295–300.
Carter M. & Bentley S.P. (1991) *Correlation of Soil Properties*. Pentech Press, London.
Casagrande A. (1932) Research on the Atterberg limits of soils. *Public Roads*, **13**, 121–130.
DIN 4094-4 (2002) Baugrund - Felduntersuchungen - Teil 4: Flügelscherversuche. Beuth Verlag GmbH (in German).
DIN 18122 (1997) Baugrund, Untersuchung von Bodenproben - Zustandsgrenzen (Konsistenzgrenzen) - Teil 1: Bestimmung der Fließ- und Ausrollgrenze. Beuth Verlag GmbH (in German).
DIN 18121 (2012) Baugrund, Untersuchung von Bodenproben - Wassergehalt - Teil 2: Bestimmung durch Schnellverfahren. Beuth Verlag GmbH (in German).
DIN 18127 (2012) Baugrund, Untersuchung von Bodenproben – Proctorversuch. Beuth Verlag GmbH (in German).
Egashira K. & Ohtsubo M. (1982) Smectite in marine quick-clays of Japan. *Clays and Clay Minerals*, **30**, 275–28.
Federico A. (1983a) Relationships (C_u–w) and (C_u–s) for remolded clayey soils at high water content. *Rivista Italiana di Geotecnica*, **17**, 38–41.
Federico A. (1983b) A comment on undrained residual strength. *Rivista Italiana di Geotecnica*, **17**, 164–166.
Feng T.W. (2004) Using small ring and a fall-cone to determine the plastic limit. *Journal of Geotechnical and Geoenvironmental Engineering*, **130**, 630–635.
Harison J.A. (1988) Using the BS cone penetrometer for the determination of the plastic limit of soils. *Geotechnique*, **38**, 433–438.
Haigh S.K., Vardanega P.J. & Bolton M.D. (2013) The plastic limit of clays. *Geotechnique*, **63**, 435–440.
Koumoto T. & Houlsby G.T. (2001) Theory and practice of the fall cone test. *Geotechnique*, **51**, 701–712.
Kuriakose B., Abraham B.M., Sridharan A. & Jose B.T. (2017) Water content ratio: An effective substitute for liquidity index for prediction of shear strength of clays. *Geotechnical and Geological Engineering*, **35**, 1577–1586.
Locat J. & Demers D. (1988) Viscosity, yield stress, remolded strength, and liquidity index relationships for sensitive clays. *Canadian Geotechnical Journal*, **25**, 799–806.
Mitchell J.K. & Soga K. (2005) *Fundamentals of Soil Behavior*. John Wiley and Sons, Hoboken New Jersey, USA.
Nagaraj H.B., Sridharan A. & Mallikarjuna H.M. (2012) Re-examination of undrained strength at Atterberg Limits water contents. *Geotechnical and Geological Engineering*, **30**, 727–736.
Norman L.E.J. (1958) A comparison of values of liquid limit determined with apparatus having bases of different hardness. *Geotechnique*, **8**, 79–83.
Ola S.A. (1978) The geology and Geotechnical properties of the black cotton soils of Northeastern Nigeria. *Engineering Geology*, **12**, 375–391.
Rajasekaran G., Essaku S. & Mathews P.K. (1994) Physico-chemical and mineralogical studies on cochin marine clays. *Ocean Engineering*, **21**, 771–778.
Schofield A.N. & Wroth C.P. (1968) *Critical State Soil Mechanics*. McGraw Hill, London.
Skempton A.W. & Northey R.D. (1953) The sensitivity of clays. *Getechnique*, **3**, 30–53.
Skopek J. & Ter-stepanian G. (1975) Comparison of liquid limit value determined according to Casagrande and Vasilev. *Geotechnique*, **25**, 135–136.
Stone K.J.L. & Phan K.D. (1995) Cone penetration tests near the plastic limit. *Geotechnique*, **45**, 155–158.
Strozyk J. & Tankiewicz M. (2013) Undrained shear strength of the heavily consolidated clay. *Annals of Warsaw University of Life Sciences – SGGW Land Reclamation*, **45**, 207–216.
Touiti L., Bouassida M. & Van Impe W. (2009) Discussion on Tunis soft soil sensitivity. *Geotechnical and Geological Engineering*, **27**, 631–643.
Towner G.D. (1973) An examination of the fall cone method for the determination of some strength properties of remoulded agricultural soils. *European Journal of Soil Science*, **24**, 470–479.
Wasti Y. & Bezirci M.H. (1986) Determination of the consistency limits of soils by the fall cone test. *Canadian Geotechnical Journal*, **23**, 241–246.

Whyte I.L. (1982) Soil plasticity and strength: a new approach using extrusion. *Ground Engineering*, **15**, 16–24.

Yosuke T., Govo I. & Masaaki K. (2004) Relationship between vane shear strength and water content for ultra-soft clay grounds showing water content decrease with depth. *Japanese Society of Civil Engineers*, **778**, 99–110.

Yukselen Y. & Kaya A. (2006) Prediction of cation exchange capacity from soil index properties. *Clay Minerals*, **41**, 827–837.