REAPPRAISAL OF THE ACTIVITY OF CLAYS. ACTIVITY CHART

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ABSTRACT

The proposed activity chart, which aims to classify soils ($< 425 \mu\text{m}$) using the Atterberg limits, differs from the plasticity chart recently proposed by the author because the inorganic soils with platy clay minerals are classified (in addition to clay percentage) on the basis of their activity rather than on the degree of plasticity as a function of the liquid limit value, currently used by the standards. This is because soils that have the same liquid limit value may have very different characteristics because of both the amount and type of clay minerals contained in the soils. On the activity chart, the silt and the clay zones are subdivided (by two straight lines) in three new groups (low activity, medium activity and high activity) making it possible to classify inorganic soils with platy clay minerals (or their fraction) $< 425 \mu\text{m}$ on the basis of the amount and type of clay minerals they contain. The activity chart adapted to predict residual shear behaviour of cohesive soils is also shown. Finally, the distinction between coarse-grained soils and fine-grained soils based on their percentage of clay ($< 2 \mu\text{m}$), might be useful in characterizing and predicting soils' engineering behaviour.

Key words: Atterberg limits, clay, laboratory tests, plasticity, residual strength, soil classification (IGC: D1/D3/D6)

INTRODUCTION

Soil properties and their engineering behaviour, apart from stress history, are markedly influenced by the physicochemical characteristics of the constituent clay and non-clay minerals and their relative proportions. Generally, two fractions with different behaviours can be distinguished in clayey soils. The “active, binder” fraction composed of clay mineral particles (which in routine assessments of soil properties, is conventionally assumed to be constituted by particles $< 2 \mu\text{m}$, termed clay fraction, CF) and the “inert” fraction composed of non-clay mineral (round) particles (conventionally $> 2 \mu\text{m}$).

It is known that the very different behaviour of clay and non-clay minerals can be attributed to the plasticity of the clay minerals. In fact, non-clay minerals (as quartz, feldspar, etc.) do not develop plastic mixtures with water, even when ground to sizes less than $2 \mu\text{m}$ (Casagrande, 1932). Hence, to classify soils with a high percentage of fine materials the content and type of clay minerals present also take on great importance. The Atterberg limits (Casagrande, 1932, 1958) reflect the composite effects of the soil constituents and their interactions with pore fluid. The liquid limit, W_L , the plastic limit, W_p , and their numerical difference, the plasticity index, I_p , constitute a widely used method of soil $< 425 \mu\text{m}$ characterization and classification (Casagrande, 1948; Polidori, 2003) and predicting cohesive soils' engineering behaviour.

A first distinction among soils based on their behavioural characteristics can be drawn between organic soils and inorganic soils. Inorganic soils containing platy clay minerals, namely common inorganic soils (with the same clay percentage), show similar behaviour that is very different from those containing non-platy clay minerals (characterized by high plastic limit, low plasticity index, etc.; Mitchell, 1993). Hence, the following considerations regarding the intrinsic properties are valid for inorganic soils with only platy shape clay minerals (such as kaolinite, illite, montmorillonite). Finally, the distinction between fine-grained soils and coarse-grained soils currently adopted by standards for soil classification is investigated.

THE PLASTICITY CHART AND INDEX PROPERTIES

Soil Classification using the Plasticity Chart

In a previous paper the author proposed a new plasticity chart (Polidori, 2003) to classify soils (or their fraction) $< 425 \mu\text{m}$ using the well-known Atterberg limits. In Fig. 1, all the I_p - W_L values of the inorganic soils containing platy clay minerals and $CF < 100\%$ should lie above the C-line and the distance of the points from the C-line should be inversely proportional to the clay percentage of the respective soils. The 0.5C-line allows us to distinguish the points that fall below the line, clays (soils with $CF \geq 50\%$), from the points lying above the line in the silt

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Fig. 1. Plasticity chart (after Polidori, 2003). C-line and 0.5C-line correspond to 100% CF and 50% CF ($< 2 \mu\text{m}$), respectively. CL, CH = clay zone ($CF \geq 50\%$). ML, MH = silt zone ($2-425 \mu\text{m} > 50\%$). OL, OH = organic soils. NPC = soils with non-platey clay minerals. Low plasticity (L) and high plasticity (H) based on ASTM standard (D 2487). A and B = example of two soil types

zone.

In turn, the silt zone (M) and clay zone (C) can be subdivided into groups with low (L) or high (H) plasticity, according to the ASTM standard (D 2487) when the liquid limit value is less than or greater than 50%, respectively.

In the same figure, it can be observed that an inorganic soil with $W_L < 50\%$ and a low clay size content, such as soil A, may lie in the low plasticity silt zone (ML), whereas an inorganic soil with $W_L > 50\%$ and a high clay fraction, such as soil B, may lie in the high plasticity clay zone (CH), although the plasticity index (and activity) of clay B is lower than that of silt A.

In a soil, when the clay fraction decreases, due to dilution (adding particles $2-425 \mu\text{m}$), its W_L (and I_p) also decreases to values less than 50% because the effect of the clay fraction is incorporated into the Atterberg limit values modified by dilution. Hence, the distinction between the high and low plasticity of soils (used by the standards, as ASTM and BS) as a function of the liquid limit value is indirectly based on the percentage of clay. In other words, when classification is based on the liquid limit value, the characteristics (expandability, activity) of the clay minerals contained in the soil are ignored, and the distinction based on the clay fraction occurs through the silt and clay zones, where the I_p - W_L data of the common inorganic soils should lie.

Some Considerations on the Index Properties

The type of platey clay mineral (also a function of the type of cation absorbed) may cause very strong variations in Atterberg limit values, even though the clay percentage remains the same. This can be inferred from Polidori's plasticity chart (Fig. 1). In fact, for inorganic soils (with platey clay minerals), the location of (W_L - I_p) data that lie on the (lines of constant CF) 0.5C-line and C-line depends on the characteristics of the clay minerals they contain. The lowest and highest values belong to clay miner-

als kaolinite and montmorillonite, respectively. Moreover, even soils that have the same W_L (or I_p) value may have very different characteristics because of the amount and type of their clay minerals. For example, a soil with higher silt and/or sand contents ($< 425 \mu\text{m}$), with the same liquid limit, shows an even higher plasticity index because it must contain clay minerals that are increasingly expandable as the clay fraction decreases. Therefore, it can be concluded that neither the Atterberg limits nor the clay percentage alone suffices to characterize, classify and predict fine soil behaviour. To separate the effects of the amount and type of clay minerals incorporated into the Atterberg limit values of a soil, the ratio of the plasticity index to the clay fraction, termed the activity ($A = I_p/CF$), (Skempton, 1953) is very useful.

In Polidori (2007) the interdependence among the parameters (W_L , W_p , I_p , A and CF of the tested soil) was observed for inorganic soils containing platey clay minerals and a clay percentage that was not too low (until the non-clay particles are still not in contact with one another; for details, see the cited paper). The quantitative relationship that includes these parameters, with respect to the plasticity index (in agreement to three equations reported in Fig. 1) is as follows:

$$I_p = 0.96 W_L - (0.26 CF + 10) \quad (1)$$

where it can be observed that the plasticity index of a soil is related to the liquid limit and clay fraction of the soil used for the Atterberg limits test.

Therefore, for inorganic soils that contain platey clay minerals (according to activity defined by Skempton, 1953), the activity will be:

$$A = [0.96 W_L - (0.26 CF + 10)] / CF \quad (2)$$

Both values, W_L and CF characterize the same soil fraction. Currently, to calculate the activity, Atterberg limits (of a soil $< 425 \mu\text{m}$) are related to the clay percentage of the entire soil. The possible presence of particles $> 425 \mu\text{m}$ in a soil would produce an overestimate of the activity value.

The activity depends on many factors (type of clay mineral, type of absorbed cation, pH, degree of crystallinity, etc.) and their combination provides a wide range of activity values, where the minimum and maximum values belong to the pure clay minerals kaolinite and montmorillonite (in monovalent ionic form), respectively. The higher the activity of a soil, the more important the influence of the clay fraction on the intrinsic properties and the more susceptible their values are to changes in such factors as the type of exchangeable cations and pore fluid composition.

Because the activity of a soil is equal to the ratio between plasticity index value and its percentage of clay, it is possible to obtain the values of the plasticity index as a function of the clay fraction for a given activity value:

$$I_p = A CF \quad (3)$$

Table 1. Plasticity index, I_p and liquid limit, W_L (calculated with Eqs. (3) and (4) respectively) as a function of clay fraction, CF for given activity, A values

CF	q	I_p for $A = 0.50$	W_L for $A = 0.50$	I_p for $A = 0.75$	W_L for $A = 0.75$	I_p for $A = 1.00$	W_L for $A = 1.00$	I_p for $A = 1.25$	W_L for $A = 1.25$
100	36	50	89.6	75	115.6	100	141.7	125	167.7
90	33.4	45	81.7	67.5	105.1	90	128.5	112.5	152.0
80	30.8	40	73.7	60	94.6	80	115.4	100	136.2
70	28.2	35	65.8	52.5	84.1	70	102.3	87.5	120.5
60	25.6	30	57.9	45	73.5	60	89.2	75	104.8
50	23	25	50.0	37.5	63.0	50	76.0	62.5	89.1
40	20.4	20	42.1	30	52.5	40	62.9	50	73.3
30	17.8	15	34.2	22.5	42.0	30	49.8	37.5	57.6
20	15.2	10	26.2	15	31.5	20	36.7	25	41.9
10	12.6	5	18.3	7.5	20.9	10	23.5	12.5	26.1
0	10	0	10.4	0	10.4	0	10.4	0	10.4

$CF = (\% < 2 \mu\text{m})$; $q = (0.26CF + 10)$; I_p and W_L are in %

Fig. 2. Relationship among plasticity index, I_p , liquid limit, W_L and clay fraction, CF ($< 2 \mu\text{m}$), for activity, A values 0.75 and 1.25 shown in Table 1. The bold lines define three zones with different ranges of activity values. The thin lines connect (I_p - W_L) data with the same CF ranging 10%

The liquid limit from Eq. (1) is:

$$W_L = (I_p + q)/0.96 \quad (4)$$

where $q = (0.26CF + 10)$. For inorganic soils with platy clay minerals Eqs. (3) and (4) make it possible to obtain the plasticity index and then the liquid limit values when the clay percentage and activity values are known. Table 1 shows liquid limit values and their corresponding plasticity index values as a function of clay fraction for some activity values. Using the activity values 0.75 and 1.25, Skempton (1953) classified clays into three groups: *inactive* clays ($A < 0.75$), *normal* clays (A 0.75 to 1.25) and *active* clays ($A > 1.25$).

In Fig. 2 the thin lines connect the (I_p - W_L) values with the same CF , ranging 10% and clearly those corresponding to $CF = 50\%$ and $CF = 100\%$ have the same equations of the 0.5C-line and C-line, respectively, according to Eq. (1). The same figure, on the basis of the values of I_p and W_L (for Skempton's activity values 0.75 and 1.25) reported in Table 1, shows two bold straight lines making it possible to distinguish three zones, located

Table 2. Activities of clay minerals, from Mitchell (1993)

Mineral	Activity
Montmorillonite	1-7
Illite	0.5-1
Kaolinite	0.5 ^(*)

(*) < 0.5 according to author

below, between and above the two boundaries, where the soils with: *low* activity, *medium* activity and *high* activity should lie, respectively. The author's activity classification differs from that proposed by Skempton (1953). The term "low" activity replaces the term "inactive" because it appears to be more suitable for distinguishing the non-plastic soils (not plotted on the chart). Note that a soil with a liquid limit greater than 100% (Fig. 2) can be classified as an "inactive" clay, according to Skempton's classification. In Fig. 2, the zone where the soils with medium activity should lie (located between bounds $A = 0.75$ and $A = 1.25$) is rather narrow compared with the low and high activity zones and no particular physical significance appears attributable to the boundaries adopted. In agreement with the range of values of the clay minerals shown in Table 2, two boundaries for the lowest activity values might be more useful (also to distinguish the sliding shear behaviour of clays, see below). On the activity chart (Fig. 3) such bounds, termed L-line and H-line, are proposed for the values $A = 0.5$ (which is the value of a subgroup noted by Skempton, 1953) and $A = 1.0$, respectively. Hence, soils containing mostly kaolinite and montmorillonite clay minerals (regardless of the clay percentage they contain) should lie in the low activity zone and in the high activity zone, respectively.

ACTIVITY CHART

On the basis of the interdependence of the parameters W_L , W_p , I_p , A and CF , it seems appropriate to classify the inorganic soils with platy clay minerals according to both their clay size content and activity. Figure 3 shows the activity chart which classifies soils using the Atterberg limits. The difference between this chart and Polidori's plasticity chart (Fig. 1) lies in the two new boundaries that define three zones with different ranges of activity values (instead of boundary at $W_L = 50\%$, according to the ASTM standard, D 2487).

All the plasticity index values of the inorganic soils with platy clay minerals and $CF < 100\%$ should lie above the C-line and the distance of the points from the C-line should be inversely proportional to clay percentage of the respective soils. The 0.5C-line allows us to distinguish the points that fall below the line, clays (C), from the points lying above the line in the silt zone (M). The clay zone is found between the C-line and the 0.5C-line and inorganic soils with $CF \geq 50\%$ should be found here. The silt zone is located between the 0.5C-line and the U-line and inorganic soils composed of silt and/or sand ($2-425 \mu\text{m}$) $> 50\%$ should lie here. The L-line and the H-line (for $A = 0.5$ and

Fig. 3. Activity chart. C-line, 0.5C-line: lines on which plasticity index, I_p , values should lie as a function of liquid limit, W_L , of inorganic soils (with platy clay minerals) that contain 100% CF and 50% CF ($< 2 \mu\text{m}$) respectively. U-line: upper limit of existence of soils. H-line, L-line: lines on which I_p values should lie (against W_L), of inorganic soils with 1.0 and 0.5 values of activity, respectively. CL, CM, CH = groups of clays ($CF \geq 50\%$) with low, medium and high activity, respectively. ML, MM, MH = groups of silts ($2-425 \mu\text{m} > 50\%$) with low, medium and high activity, respectively. O = organic soils. NPC = soils with non-platy clay minerals. (A and B: soils data from Fig. 1)

$A = 1.0$, respectively) subdivide the silt and clay zones into three groups: low activity (L), medium activity (M) and high activity (H), located, below, between and above the two boundaries, respectively.

The residual inorganic soils (NPC) composed of non-platy clay minerals (allophane, halloysite, attapulgite) should lie below the C-line because their characteristics (high plastic limit, low plasticity index, high residual strength, etc.; Kenney, 1967; Wesley, 1973; Skempton, 1985; Mitchell, 1993; Rao, 1996; So, 1998) are very different from those of platy clay minerals for which the activity chart was developed. The soils (NPC) that contain both platy and non-platy clay minerals as well as the organic soils (O) can lie above or below the C-line according to characteristics and proportions of the soil constituents.

Characterizing the soils containing non-platy clay minerals is not always easy, and estimating both the contents (if present) of platy and non-platy clay minerals in the same soil is impossible in routine assessments of soil properties. Nevertheless, even if the non-platy clay minerals in the clay fraction of a soil are not identified as such, in engineering problems their presence makes the soil "safer" because the intrinsic mechanical properties of residual clay minerals (e.g., the residual friction angle) are better than those of the platy clay minerals.

From a behavioural standpoint, an organic soil contains sufficient organic matter to influence the liquid limit (and other soil properties). Hence, if a soil shows the distinctive characteristics of an organic substance (such as: dark colour, characteristic smell when moist and warm,

reacts to hydrogen peroxide, etc.). a second liquid limit test should be performed on a soil specimen which has been oven dried at 105°C . It will be classified as an organic soil if the liquid limit after oven drying is less than 95% of the liquid limit determined before oven drying. Further study and new experimental data are desirable to understand which value is more suitable: the proposed value (95%) or a lesser value (e.g., 90%). Note that the Atterberg limits of both soil types (O-NPC) are not governed by CF linear law. Hence, their plastic limit can be determined only through the W_p standard test (and not using Eq. (5), see below).

The possible distinction (low and high plasticity, not shown in Fig. 3) for soils that lie below the C-line could be more useful based on the plasticity index value rather than on the liquid limit value.

Applying the proposed classification method, for example, plotting the data of the two soils shown in Fig. 1 in Fig. 3, soil A is classified as a "silt with high activity" instead of a "silt with low plasticity" and soil B is classified as a "clay with low activity" instead of a "clay with high plasticity".

Soils containing only Platy Shape Clay Minerals

The Atterberg limits governed by linear law to CF are of fundamental importance in characterizing and obtaining correlations with the intrinsic mechanical properties of soils because they show the soil's behaviour dominated by the clay phase. On the contrary, when the volume of the clay water system in a sample soil is equal to or lesser

than the volume of the voids of the non-clay phase (when the non-clay particles are in contact with one another due to low CF in the soil-water system) the Atterberg limits—if determinable—are no longer ruled by CF linear law because the behaviour of the soil is dominated by the granular phase characteristics.

It may not be a simple task to determine the soil's physical state because the determination of the void ratio of the fraction $>2\mu\text{m}$ of a soil (necessary to estimate the voids' volume in the granular phase) is cumbersome and time consuming. Nevertheless, if the clay percentage in the soil fraction passing the No. 40 ($<425\mu\text{m}$) sieve is low ($CF < 25\text{--}30\%$), the Atterberg limits can be performed on a soil fraction with a diameter that is less than that passing the No. 40 sieve. Hence the Atterberg limit values that should correspond to the clay percentage of the soil passing the No. 40 sieve (and for any other CF) can be appraised (using Eqs: $W_L = k_1 CF$ and $W_p = (k_2 CF) + 10$, where k_1 and k_2 are the slopes).

It is known that every measured data has some margin of error. In fact, the interrelationship among the parameters W_L , W_p , I_p , A and CF (on which the proposed chart is based) was obtained on the basis of the average values (using the equations of the regression lines) of the Atterberg limits governed by CF linear law (performed according to ASTM standards, D 4318 and D 422). The quantitative relationship with respect to the plastic limit is:

$$W_p = 0.04 W_L + (0.26 CF + 10) \quad (5)$$

Equation (5) can replace the W_p standard test if the values linearly proportional to the W_L and CF of the tested soil are known.

Since the parameters are linked with one another, at a given W_L value (on the activity chart), the W_p measured value (through I_p), the activity value and the value of the percentage of clay of the tested soil $<425\mu\text{m}$ should correspond. Hence this value of CF , appreciable on the chart (or analytically calculable), should be (approximately) equal to the clay percentage of the grain size distribution of the soil fraction $<425\mu\text{m}$ used in the Atterberg limits test. If the difference between the measured and calculated values is considerable, it would be useful to understand the causes of the discrepancy (e.g., standard tests performed incorrectly, the presence of non-platey clay minerals in the sample soil tested, etc.).

In Figs. 4, 5, 6 and 9 both the values of the plasticity index (measured and calculated) being compared are plotted. In Figs. 6 and 9 the calculated values of I_p are based on the CF value reported by the authors, assuming that both the clay contents of the entire soil and the soil used for the Atterberg limits test are equal.

Considering: (i) the poor precision of the standard method for determining the plastic limit (Whyte, 1982; Polidori, 2007) and, (ii) the link between W_p and CF in Eq. (5) (an error of 10% on the CF value produces an error of 2.6 units on the W_p value, or *vice versa*), it is possible to assert that the measured values of W_L and CF (linearly proportional) of the soil tested (to obtain W_p , I_p

and A) are more suitable than the measured values of W_L and W_p (to obtain CF , I_p and A). It is evident that (among the measurable parameters W_L , W_p , CF), the liquid limit test is of fundamental importance. Casagrande's method for determining the liquid limit is an easy reproducible test. For example, Sridharan et al. (1986, 1988) reported that the variation between two trials was about 1%.

EXAMPLES OF SOILS PLOTTED ON THE ACTIVITY CHART

In Fig. 4 the values of the plasticity index (measured and calculated) are plotted as a function of the liquid limit of the pure clay mineral kaolinite, bentonite and their mixtures as shown in Table 3. Since all of the mixtures are composed of 100% clay, all the respective values of the plasticity index should lie on the C-line (regardless of any possible chemical interaction among the constituents). Pure kaolinite and the mixture with 75% kaolinite lie in the low activity clay zone and medium activity clay zone, respectively, whereas the other mixtures with 50% or more bentonite lie in the high activity clay zone. The same mixtures plotted on the plasticity chart (Fig. 1) would all lie in the high plasticity clay zone. As expected, values of residual soils (with non-platey clay minerals) lie below the C-line independently of their clay percentage.

Figure 5 shows the data of the clay minerals illite (with

Fig. 4. Location on proposed activity chart (see Fig. 3) of data from literature (Table 3). Casagrande's A-line also shown

Table 3. Index properties of clay minerals (K=kaolinite; B=bentonite) and their mixtures, from Di Maio and Fenelli (1994). I_p (c) = plasticity index calculated with Eq. (1)

Soil	CF	W_L	I_p	I_p (c)
K	100	57.5	19.7	19.2
75%K-25%B	100	100.9	63.5	60.9
50%K-50%B	100	165.3	127.5	122.7
40%K-60%B	100	205.5	161.2	161.3
25%K-75%B	100	259.2	210.3	212.8
B	100	330.6	275.4	281.4

$CF = (\% < 2\mu\text{m})$; W_L and I_p are in %

Fig. 5. Location on proposed activity chart (see Fig. 3) of data from Seed et al. (1964). I_p calculated with Eq. (1) and Casagrande's A-line also shown

Table 4. Index properties of natural soils taken from Lupini et al. (1981). I_p (c) and A (c), values calculated with Eqs. (1) and (2) respectively

Soil no.	CF	W_L	I_p	I_p (c)	A	A (c)
1	55	71	43	44	0.78	0.80
2	43	59	31	35	0.72	0.81
3	50	57	33	32	0.66	0.64
4	32	26	6	6	0.19	0.19
5	32	31	12	12	0.37	0.37
6	52	65	33	39	0.63	0.75
7	63	63	35	34	0.55	0.54
8	47	59	33	34	0.70	0.72
9	50	59	29	34	0.58	0.68
10	51	63	37	37	0.73	0.73
11	48	75	51	50	1.06	1.04
12	48	73	49	48	1.02	1.00
13	36	57	36	36	1.00	1.00
14	57	72	43	44	0.76	0.77
15	59	95	61	66	1.03	1.12
16	57	82	54	54	0.95	0.95
17	53	66	42	40	0.79	0.75
18	64	68	43	39	0.67	0.61
19	46	62	36	38	0.78	0.82
20	50	85	58	58	1.16	1.16
21	52	58	32	32	0.62	0.62
22	51	59	36	33	0.71	0.65
23	60	93	61	64	1.02	1.07
24	50	94	60	67	1.20	1.34
25	38	41	20	20	0.53	0.53
26	46	63	38	38	0.83	0.83

CF = (% < 2 μ m); W_L and I_p are in %

CF=35%), bentonite (with CF=95%) and their mixtures (Seed et al., 1964). The I_p values of the illite and mixtures (containing 95% and 80% illite) with CF<50% lie in the medium activity silt zone, whereas data of the mixtures with the highest bentonite content (and CF>50 %) lie in the high activity clay zone. The same soils plotted on the plasticity chart (Fig. 1) would lie in the high plasticity clay zone, except illite which would lie in the low plasticity silt zone.

Table 4 shows the data (including the calculated values of I_p and A) of natural soils (except the soils with CF<30

Fig. 6. Location on proposed activity chart (see Fig. 3) of natural soils shown in Table 4. I_p calculated with Eq. (1) and Casagrande's A-line also shown. A = activity

% and the residual soils) taken from Lupini et al. (1981). These soils are plotted in Fig. 6 where they are subdivided into three groups as a function of their measured activity values. The soils with measured plasticity index values which are different from those calculated with Eq. (1), have clay percentages (appreciable on the graph or analytically calculable with equation: $CF = [(0.96W_L - I_p) - 10]/0.26$ obtained from Eq. (1)) which differ from those reported by the authors. Hence, some soils may lie in a zone that does not correspond to their CF and/or their activity value. For example, soils no. 15, 23 and 24 have activity values that are greater than 1 and therefore should not lie in the medium activity clay zone (of grey color).

For 21 soils (of the 26 soils plotted) the difference between both the activity values (Table 4) is rather small (average value <0.02). If both the clay fractions are equal (of the entire soil and the soil <425 μ m used for the Atterberg limits test) and organic substances and non-platy clay minerals are absent, the causes of the discrepancy between the (I_p and A) measured and calculated values may be mainly attributable to the poor precision of the standard method for determining the plastic limit.

In Figs. 4–6 the A-line ($I_p = 0.73(W_L - 20)$; Casagrande, 1948) has also been included in order to show where the same soils (of different types) would lie on Casagrande's plasticity chart, since the respective positions of the silt and clay zones appear reversed on the two charts. Only the data of the residual soils (Fig. 4) containing non-platy clay minerals and (amiss) kaolinite fall below the A-line in Casagrande's silt zone. The position of the A-line is such that the common inorganic soils (containing platy clay minerals), except relatively pure kaolinite, lie above it in the clay zone regardless of their clay percentage. In fact, in a previous paper (Polidori, 2007) of 125 soil samples plotted, only 3 kaolinite soils lie below the A-line in the silt zone (according to Casagrande). The same occurs, for example, in the paper by Nagaraj and Jayadeva (1983) where 520 soil samples are plotted on Casagrande's plasticity chart. All soils lie above the A-line in the clay zone, except for the data of 3

soils that lie below the A-line in Casagrande's silt zone. Hence, it is evident that the boundary A-line is equivalent to Polidori's C-line because the residual soils lie below both the boundaries. It therefore appears more accurate to affirm that on the empirical plasticity chart proposed by Casagrande, no distinction (silt zone) exists above the A-line where the common soils lie. In essence (since the behaviour of a soil, in addition to the type of clay minerals, etc., also depends on the clay percentage), it can be concluded that Casagrande's chart does not suffice to classify and predict engineering behaviour (such as residual shear behaviour) of soils containing platy clay minerals.

ACTIVITY CHART TO PREDICT RESIDUAL SHEAR BEHAVIOUR OF COHESIVE SOILS

Correlations making use of the index properties are fairly common in soil mechanics literature, especially to estimate the compression index and drained residual strength friction angle, ϕ'_r of fine-grained soils. In addition, the proposed activity chart can be useful for this purpose. The activity chart adapted to estimate the drained residual shear behaviour of inorganic soils containing platy clay minerals is shown herein. Clearly, the following considerations are not valid for non-platy clay minerals (halloysite, allophone, attapulgite) that exhibit residual friction angles close to that of round particles, usually greater than 25° (Kenney, 1967; Wesley, 1977).

Various attempts have been made to correlate the residual strength friction angle of cohesive soils with their index properties such as the liquid limit, plasticity index, activity and clay fraction (Skempton, 1964, 1985; Kenney, 1967, 1977; Voight, 1973; Kanji, 1974; Seycek, 1978; Vaughan et al., 1978; Lupini et al., 1981; Mesri and Cepeda Diaz, 1986; Collotta et al., 1989; Stark et al., 1994; Wesley, 2003; Dewoolkar and Huzjak, 2005; and others).

Skempton (1985) investigated the drained residual strength of some English clays and compared field and laboratory values, contributing a valuable update on residual shear strength and supporting the three residual shear behaviours shown by Lupini et al. (1981). The main points carried out by Skempton are as follows:

- Residual friction angle of a soil (for a given normal effective pressure) depends on its clay percentage and type (activity) of platy clay mineral (Fig. 7). Specifically, if the clay fraction in a soil is less than about 25 %, the soil behaves much like a sand or silt with angles of residual shearing resistance typically greater than 20° (*Rolling shear*). Conversely, when the clay fraction in a soil is about 50%, residual strength is controlled almost entirely by sliding friction of the platy clay minerals (*Sliding shear*), and further increase in CF has little effect. When the clay fraction lies between 25% and 50%, there is a *Transitional shear* involving both rolling and sliding shear mechanisms in different parts of a shear zone.
- For most soils the relation between residual strength

Fig. 7. Dependence of residual friction angle, ϕ'_r by clay fraction, CF and activity, A , according to Skempton (1985). ϕ'_r - CF data of samples plotted in Figs. 8 and 9 also shown

and normal effective pressure is non-linear and the variation in the degree of curvature between one soil and another can be considerable.

In Fig. 8 three zones that correspond to three cited modes of residual shearing behaviour: *Rolling shear*, *Transitional shear* and *Sliding shear* (from U-line to C-line, respectively) are shown. In turn, the sliding shear zone is subdivided into three sub-zones (as a function of the range of the activity values) as shown on the activity chart. The boundaries that define the transitional zone are according to Eq. (1). The average values of the clay percentage ($CF=25\%$ and $CF=45\%$) which define such a range, are in agreement with Skempton (1985) and the author's study in progress. The residual friction angle range values expected for the soils that lie in these zones and sub-zones (where $\phi'_r = 12^\circ-15^\circ$ and $\phi'_r = 4^\circ-10^\circ$ are expected for soils containing mainly kaolinite and montmorillonite clay minerals, respectively (Skempton, 1985; Mitchell, 1993)) are also shown.

From Fig. 8 it can be inferred that, for soils with the same I_p value, ϕ'_r is expected to decrease as W_L increases (from rolling shear to sliding shear zones) and for soils with the same W_L value, ϕ'_r is expected to increase as I_p increases (from sliding shear to rolling shear zones). Hence, it is obvious that the correlations based on either W_L or I_p do not provide good estimates of the drained residual friction angle. The correlation ϕ'_r - CF seems more appropriate than ϕ'_r - I_p (and ϕ'_r - W_L), but is not enough to obtain reliable ϕ'_r values for engineering purposes.

The drained residual strength behaviour is strongly dependent on the distance among the round particles contained in a soil. Specifically, in a normal consolidated soil at a given normal effective pressure, this distance is mainly a function of the amount and type of platy clay minerals (chemical state enclosed) and of the granular phase void ratio. When both the volume of the clay-water system and that of the voids of the granular phase are equal, the non-clay particles are in contact with one another.

The characteristics of the soil granular phase (such as the void ratio, size-shape of the particles, gradation, etc.)

Fig. 8. Activity chart adapted to predict residual shear behaviour of cohesive soils containing platy clay minerals. Mixtures of bentonite-sand and kaoninite-sand are also shown. The $I_p - W_L$ values belonging to bentonite-sand mixture with the lowest CF value ($CF=13\%$, $\phi_r'=30^\circ$) should not lie on transitional zone (see text). ϕ_r' (24°) = drained residual friction angle (value in degrees)

and their effect on ϕ_r' , cannot be known through the Atterberg limit values. Nevertheless, plotting the ($I_p - W_L$) data of soils in Fig. 8, a reduction in residual friction angle with the increase of the clay percentage from that of a soil involving rolling shear without preferred particles orientation (high ϕ_r'), to that of pure platy clay minerals, involving sliding shear (low ϕ_r'), is expected. In turn, in the sliding shear zone (that contains the soils in which the round particles are scattered in the clay-water system), the more active the clay fraction, the lower the residual friction angle at a given clay percentage and a given confining pressure.

In conclusion, for the common inorganic soils ($<425 \mu m$), the plotting of the Atterberg limits data on the activity chart allows us to make a better appraisal of the residual shear behaviour than the predicted correlations. This is because the residual shear strength is related to all the interdependent parameters (W_L , I_p , A and CF) on which the chart is based.

It is worth noting that the same sample preparation procedure (standard) and the same apparatus (direct shear box or ring shear tests) should be used to better compare (or develop correlations between) property data of soils. In addition, both the clay fractions (of the sample used for residual shear test and of that used for Atterberg limit test) should be equal (both passing the No. 40 ASTM sieve) to obtain methodically accurate relations.

In Fig. 8, the Atterberg limits of the mixtures of bentonite-sand and kaoninite-sand are plotted with the relative residual friction angle values ($\phi_r' = \tan^{-1}(\tau_r'/\sigma')$, where τ_r' is the residual strength at a normal effective pressure, $\sigma' = 350$ kPa). Direct shear box and ring shear tests

were used for kaolinite and bentonite, respectively. Note when in a sample soil the non-clay particles are in contact with one another (rolling shear behaviour should occur) and the Atterberg limits values are no longer ruled by the CF linear law because the behaviour of the soil is dominated by the granular phase characteristics. Hence soils found in this physical state can lie within rolling shear zone or below in the transitional zone. This is shown in Fig. 8 for the bentonite-sand mixture which is characterized by the lowest clay fraction ($CF=13\%$, $\phi_r'=30^\circ$). The residual friction angle values of the remaining mixtures are in good agreement with those of the zones on which the data lie.

Figure 9 shows the index properties and ϕ_r' values of some English clays and of Happisburgh clay-London clay mixtures (normally consolidated at $\sigma' = 150$ kPa and $\sigma' = 350$ kPa, respectively) taken from literature. Direct shear box for the English clays and ring shear tests for the cited mixtures, were used. It can be observed that, the ϕ_r' values are in better agreement with the location of the I_p calculated values rather than the location of the I_p measured values. This confirms the validity of the quantitative interrelationship proposed.

Correlations to obtain a reliable value of ϕ_r' from index properties of a soil should not be tenable for two main reasons (regardless of the procedure and apparatus used): (i) the different role played by the granular phase (that is a passive role of inert fill in the Atterberg limits test), (ii) the influence of normal effective stress acting on the shear zone. As a consequence, soils with the same Atterberg limit values (linearly proportional to CF) can show different ϕ_r' resulting from their granular phase characteristics

Fig. 9. Location on the adapted activity chart to predict residual shear behaviour (see Fig. 8) of natural soils. R, T and S = Rolling, Transitional and Sliding shear zones, respectively. ϕ'_r (19°) = drained residual friction angle (value in degrees). I_p calculated with Eq. (1) also shown

(particularly for soils that lie in transitional zone) and/or from normal stress acting on their failure plane. In addition, more values of ϕ'_r can also correspond to a single soil as a function of the confining pressure applied. Indeed, Skempton (1985) suggested that it is better to compare soils' ϕ'_r values achieved at the same pressure. This means that, in terms of CF , the range of the transitional zone depends on both the granular phase characteristics and the normal stress. Nevertheless, the location of soils data (I_p - W_L) on the activity chart is useful for understanding the corresponding residual shear behaviour and the expected range of ϕ'_r values. The activity chart used for this purpose should not replace site-specific laboratory determination of residual shear strength. Instead, it can be useful in selecting samples for laboratory residual strength tests. If the difference between both the residual friction angle values (the experimental value and that which is inferred from the range on the activity chart) is noticeable, it would be better to understand the causes of the discrepancy (e.g., presence of particles $>425 \mu\text{m}$ in the sample for residual shear test or the presence of non-platey clay minerals; partial disruption of the samples on which the index tests were performed, sometimes such disruption can increase during the shear displacement and platey clay particles may be generated; etc.).

Further study and new experimental data are necessary to understand the meaning of the different degree of curvature of the residual shear envelope between one soil and another.

FINE AND COARSE SOILS CLASSIFICATION

In order to classify soils, according to the current ASTM standard (D 2487), the distinction between coarse-grained soils and fine-grained soils is based on the percentage by dry weight ($<50\%$ and $\geq 50\%$, respectively) of the test specimen passing the No. 200 ($75 \mu\text{m}$) sieve. Coarse-grained soils are classified primarily by grain size

Fig. 10. Example of grain size distribution of two soils classified according to ASTM standard (D 2487). The soils with the granulometric curves that lie above and below the point plotted are classified as fine-grained and coarse-grained soils, respectively. The fine-grained soil, with a very low clay fraction, can not be characterized with the predicted plasticity tests

distribution of particles $>75 \mu\text{m}$ (sand or gravel whichever is predominant), while fine-grained soils are classified primarily by plasticity characteristics of the soil fraction $<425 \mu\text{m}$.

Hence, a soil with a high percentage ($>50\%$) of particles passing the No. 200 sieve and a very low (or absent) clay percentage is classified as a "fine-grained soil," whereas its behaviour should be (not plastic, similar to that expected for coarse-grained soils) dominated by the characteristics of the non-clay size particles. The contrary can occur when in a coarse soil the percentage of the non-clay particles ($2-75 \mu\text{m}$) is very low and the clay percentage is relatively high. Figure 10 shows an example of possible grain-size distribution of fine and coarse soils as described above. Note that a fine soil with the clay fraction absent or very low (such as the fine soil shown in Fig. 10) cannot be characterized using the predicted Atterberg limits. In addition, if a soil is composed only of silt particles, it cannot be classified following fine-grained soils procedure (Atterberg limits) or coarse-grained soils procedure (sieves). This can also occur using other standards.

Since the behaviour of a soil (in addition to the type of clay minerals, etc.) also depends on the clay percentage, the distinction between coarse soils and fine soils based on their percentage of clay ($<2 \mu\text{m}$), might be more useful. The percentage of clay in a soil is an important parameter. For example, Skempton (1964, 1985) concluded that there is better correlation between the residual friction angle and the clay percentage of a soil rather than its Atterberg limits. The author's opinion is that both the clay percentages (of the fraction $<425 \mu\text{m}$ and of the entire soil) together with the Atterberg limits are of importance in order to characterize inorganic soils with platey clay minerals and to obtain correlations with the intrinsic mechanical properties of the soils. Note that for common inorganic soils, the clay percentage can be appraised without performing the hydrometer analysis of

the test sample. Specifically, from Atterberg limits of a soil, the clay percentage of the tested soil ($< 425 \mu\text{m}$) can be analytically calculated (or graphically estimated plotting Atterberg limits data on the activity chart). The clay percentage of the entire soil can then be determined, if the percentage of the soil retained on the No. 40 ($425 \mu\text{m}$) sieve, which is excluded from Atterberg limits characterization, is known.

The alternative way (more laborious but more appropriate) is: knowing only W_L and CF (linearly proportional) of the soil tested, the W_p , I_p and A values can be calculated.

CONCLUSIONS

The proposed activity chart (W_L , I_p), which aims to classify soils (or their fraction) $< 425 \mu\text{m}$ using the Atterberg limits, differs from the plasticity chart previously proposed by the author because the inorganic soils with platey clay minerals are classified (in addition to clay percentage) on the basis of their activity rather than on their plasticity (low or high plasticity when the liquid limit value is less than or greater than 50% respectively, according to ASTM standard). Hence, the activity chart proposed (based on the interdependence among the parameters, W_L , W_p , I_p , A and CF of the tested soil), appears more suitable because the classification (silt and clay, in turn with low activity, medium activity and high activity) of common inorganic soils ($< 425 \mu\text{m}$) is based on the amount and type of platey clay minerals and the two effects are incorporated into the Atterberg limit values of the tested soil.

Correlations to obtain a reliable value of the residual friction angle from the index properties values of cohesive soils appear untenable. Nevertheless, the location of Atterberg limits data on the (adapted) activity chart to predict drained residual strength behaviour of inorganic soils containing platey clay minerals proves more suitable than the existing correlations. The activity chart used for this purpose should not replace laboratory determination of residual shear strength, but it can be applied as follows:

- a) to infer the residual shear behaviour of the soils ($< 425 \mu\text{m}$) and the expected range of residual friction angle values;
- b) to select samples for laboratory residual strength tests;
- c) to compare both the residual friction angle values (the experimental value and that which is inferred from the activity chart). If the difference is noticeable, we should try to understand the causes of the discrepancy.

Considering the very different behavioural characteristics of the soil constituents (conventionally attributed to fractions less than and greater than $2 \mu\text{m}$), the distinction between coarse-grained soils and fine-grained soils based on their percentage of clay ($< 2 \mu\text{m}$) (and the Activity chart proposed), might be very useful in classifying and predicting soils' engineering behaviour.

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