The cone penetration index: A simple new soil index test to replace the plasticity index

L'indice de pénétration de cône: Un nouvel essai indicateur simple sur sol pour remplacer l'indice de plasticité

L. R. SAMPSON, Senior Researcher, Soil Engineering Group, National Institute for Transport and Road Research, Council for Scientific and Industrial Research, Pretoria, South Africa
F. NETTERBERG, Head, Soil Engineering Group, National Institute for Transport and Road Research, Council for Scientific and Industrial Research, Pretoria, South Africa

SYNOPSIS The cone penetration index (I_{PC}) is defined as the numerical difference between the moisture contents at the BS 1377:1975 cone penetration depths of 20 and 5 mm (w_{20} and w_5 respectively). w_{20} is equal in all respects to the BS liquid limit and is very strongly (r = 0,99) correlated with and numerically equal to 4 units higher than the ASTM liquid limit (w_L). w_5 is strongly (r = 0,93) correlated with, but not numerically equal to the plastic limit (w_P). The I_{PC} is strongly (r = 0,93 and 0,85 respectively) correlated with, but not numerically equal to both the BS and ASTM plasticity index (I_P). The mean multilaboratory precision (reproducibility) of w_{20}, w_5 and I_{PC5} on 14 soils tested by 9 laboratories of 12, 14 and 30 D2S% respectively is significantly superior to that of the 15, 37 and 47 D2S% of w_L, w_P and I_P. These new indices are proposed as possible international standard replacements for the w_L, w_P and I_P. The advantages of such a move are discussed and are considered to outweigh the disadvantages in the long term.

INTRODUCTION

The plasticity index (I_P or PI) of a soil or soil aggregate mixture, whilst probably being one of the most widely used parameters in all fields of soil mechanics, has long been a cause for concern because of its poor precision (repeatability and reproducibility). After more than 50 years of use in engineering practice there is still no international standard for its determination. As the I_P is numerically equal to the difference between the liquid and plastic limits (w_L, w_P), it is only when the precision of both of these tests and especially that of the latter, is improved that greater confidence can be placed in the I_P.

With regard to the liquid limit test, Sherwood and Ryley (1970) and Weston (1978) showed that the drop cone penetrometer method, now incorporated in the British Standard (BS) 1377:1975 (British Standards Institution, 1975), has a multi-laboratory precision (reproducibility) considerably better than (about half of) those of the Casagrande cup liquid limit method, whether determined with a British or an American Society for Testing and Materials (ASTM) device. Various types of cone penetrometer methods are presently in use throughout the world as a substitute for the Casagrande (1932) liquid limit method (Sampson and Netterberg, 1984), but no substitute for the plastic limit method appears to have been adopted as a standard anywhere. Thus, while the plastic limit test remains a prerequisite of the I_P, no greater confidence can be placed in this parameter.

It is the intention of this paper to present the results of an investigation into the use of an extended BS cone penetrometer method as a substitute for the plastic limit thread method. Two possibilities will be considered, firstly the use of a minimum penetration moisture content as suggested by Campbell (1976) and secondly, the use of a fixed penetration as suggested by, among others, Towner (1973) and Allbrook (1980). The equivalent I_Ps obtained from the penetration curves are compared with the I_P, and the precision limits of the various tests are also reported.

MATERIALS AND TESTING

Forty-three soils and soil-aggregate mixtures from all over southern Africa representing a variety of geological origins and engineering materials with w_Ls from 20 to about 120 were used. For all soils the following tests were carried out:

1. Casagrande cup liquid limit (ASTM device with a base of hardness of 85-95 on the Shore D scale at 23 ± 2 °C) - National Institute for Transport and Road Research (NITRR) (1979) Method A2 (three point flow curve method);
2. plastic limit and plasticity index - NITRR (1979) Method A3.

   These two methods are very similar to ASTM methods D423-66 and D424-59 (ASTM, 1980a, b) although they do differ on certain points of detail. NITRR (1979) and subsequent additions and amendments are the standard methods used in road construction in South Africa.
3. Extended BS cone penetration method.

Of the forty-three soils, fourteen were also used in a reproducibility study.

Extended cone penetration method

The BS 1377:1975 (Test 2A) cone penetrometer method is used except that penetrations are carried out from the drier to the wetter state with incremental increases in moisture content from below the plastic limit to a moisture content in excess of the liquid limit (defined as that required to give 20 mm penetration). (In brief, the BS method requires a 30° angled cone of mass 80 g to sink freely into a soil paste for five seconds.) Moisture contents corresponding to penetrations at 20 mm (w_{20}, i.e. the BSw_L), 5 mm (w_5) and at the minimum penetration (w_{MP}) are then read off the plots of penetration versus moisture content so obtained. The difference between w_{20} and w_5 and w_{20} and w_{MP} is called the Cone Penetration Index (I_{PC} or CPI) i.e. I_{PC5} and I_{PCMP}, respectively. Examples of typical penetration curves are shown in Fig.1.

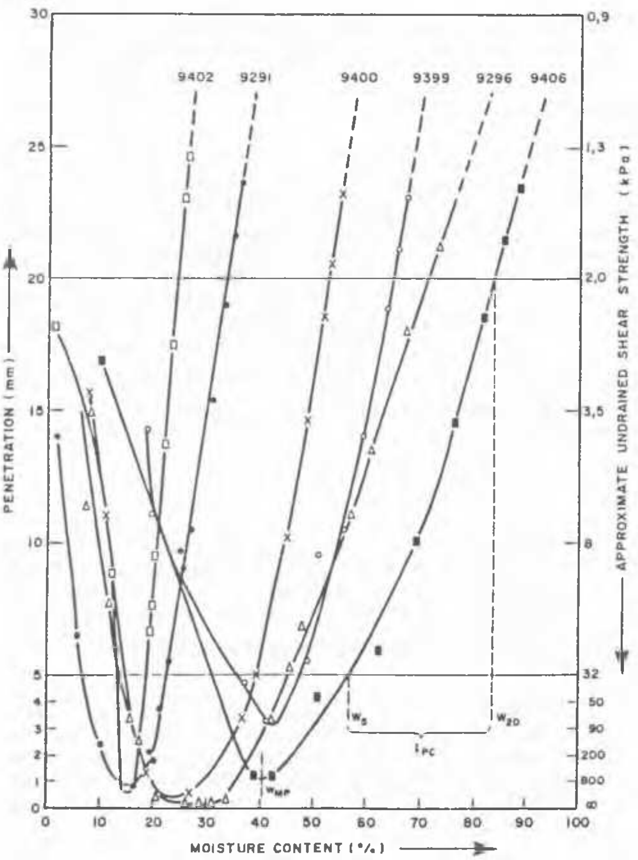

Fig.1 Moisture Content versus Penetration Curves from the drier to the wetter state

The undrained shear strengths at various penetration depths were calculated from Hansbo's (in Karlsson, 1981) formula for a 30° cone on the assumption that his constant K is equal to 10 and is independent of soil type, cone roughness, depth of penetration, etc. While this assumption is not strictly valid, it suffices to give a general indication of the shear strength (Sampson, 1983). The straight portion of such curves in the vicinity of w_L is known as a 'consistency curve' in Sweden analogous to the flow curve obtained with the Casagrande device, and a 'consistency index' analogous to the flow index can be calculated (Karlsson, 1981).

A summary of the results by the extended cone and the Casagrande method is shown in Table I.

Although South African test procedures have been followed rather than ASTM or BS unless stated otherwise, for ease of comparison the liquid limits and other parameters determined using an ASTM D423 device will be designated with the subscript 'A' (i.e. w_{LA}, I_{PA}) and those determined using a BS 1377 device with the subscript 'B' (i.e. w_{LB}, I_{PB}). Additional differences in test procedures and soil preparation methods between the three countries will add to the differences reported here, which are intended to solely represent those due to differences in liquid limit devices.

DISCUSSION

Regression analyses were carried out to obtain the correlation between the various parameters reported in Table I.

(i) Casagrande w_L versus BS cone w_L (w_{20})

The relationship for these two parameters has been well documented although care should be taken to identify which Casagrande device is used, i.e. British or American, as the base of the former is softer than that of the latter and hence yields higher results.

For the British Casagrande devices, the results between 20 and 100 liquid limit should be considered equal to the 20 mm cone penetration moisture content (BS cone w_L) (Sherwood and Ryley, 1970).

For the American (ASTM) devices the cup liquid limit (w_{LA}) is approximately 4 units lower than the cone liquid limit over the same range (Sampson and Netterberg, 1984). The results in Table I confirm this with the following linear regression equation being obtained for the range 20 to 120:

$$w_{LA} = 0,96\ w_{20} - 3,2 \qquad (1)$$

correlation coefficient (r) = 0,988, coefficient of variation (V) = 7,2 %).

This compares well with the equation for 89 results reported by Sampson and Netterberg (1984).

The best equations combining all results available to date are:

$$w_{LA} = 0,97\ w_{20} - 3,1 \qquad (2)$$

(r = 0,986; n = 123; 9 laboratories; 95 %

TABLE I

Summary of Casagrande and cone penetration test results on 43 soils (NITRR laboratory)

Sample number	Material[1]	NITRR Casagrande methods			Extended BS cone penetration method				
		w_{LA}	w_P	I_{PA}	w_{20}	w_5	w_{MP}	I_{PC5}	I_{PCMP}
9291	Calcrete sandy gravel, Nata-Kazangula	26,7	19,4	7,3	33,6	22,0	15,2	11,6	18,4
9296	Active black clay, Pretoria	67,1	32,0	35,1	69,8	44,0	29,0	25,8	40,8
9399	Weathered diabase gravel, Mabopane	62,7	37,9	24,8	64,5	47,1	42,6	17,4	21,9
9400	Weathered dolerite, Secunda	44,1	27,4	16,7	52,7	39,4	25,0	13,3	27,7
9402	Chert, NITRR	19,6	18,2	1,4	24,4	18,6	15,6	5,8	8,8
9405	Ferricrete, Witbank	26,5	24,4	2,1	30,4	26,3	23,0	4,1	7,4
9406	Weathered dolerite, Swaziland	80,0	34,3	45,7	83,7	57,0	40,4	26,7	43,3
9609	Red clayey sand, Pretoria	23,4	12,5	10,9	28,3	19,8	14,2	8,5	14,1
9610	Red clayey sand, Pretoria	25,4	13,6	11,8	30,5	22,1	17,0	8,4	13,5
9611	Red clayey sand, Pretoria	28,7	15,2	13,5	30,1	24,0	16,5	6,1	13,6
9612	Red clayey sand, Pretoria	28,1	17,8	10,3	35,2	24,5	18,5	10,7	16,7
9613	Red clayey sand, Pretoria	22,4	11,9	10,5	25,6	19,7	15,0	5,9	10,6
9614	Red clayey sand, Pretoria	26,7	14,3	12,4	30,5	21,9	14,2	8,6	16,3
9615	Red clayey sand, Pretoria	28,5	14,6	13,9	30,3	23,2	17,6	6,9	12,7
9616	Red clayey sand, Pretoria	31,0	15,4	15,6	36,5	24,5	16,6	12,0	9,9
9617	Red sandy clay, Pretoria	34,7	17,8	16,9	39,0	26,0	17,3	13,0	21,7
9618	Red sandy clay, Pretoria	35,8	20,1	15,7	37,8	29,0	19,5	8,8	18,3
9619	Red sandy clay, Pretoria	36,9	21,3	15,6	44,0	30,0	19,0	14,0	11,0
9620	Red clayey sand, Pretoria	22,3	13,9	8,4	28,7	19,6	13,7	9,1	15,0
9621	Red sandy clay, Pretoria	32,2	16,5	15,7	37,8	25,0	15,0	12,8	25,8
9622	Red sandy clay, Pretoria	35,6	17,1	18,5	40,5	27,0	16,6	13,5	23,9
9624	Brown sandy clay, Pretoria	43,3	20,0	23,3	47,9	30,6	17,7	17,3	30,2
9626	Reddish brown sandy clay, Pretoria	57,8	31,4	26,4	59,0	39,5	26,5	19,5	32,5
9627	Reddish brown sandy clay, Pretoria	53,7	27,2	26,5	56,6	36,9	25,0	19,7	31,6
9777	Sandy clay, Olifantsfontein	34,2	18,9	15,3	35,5	26,8	19,0	8,7	16,5
9779	Clay, Vereeniging	51,7	17,3	34,4	53,7	35,7	25,0	18,0	33,7
9780	Clay, Radium	59,3	22,4	36,9	60,6	43,8	24,8	16,8	35,8
9781	Active black clay, Pretoria	63,4	22,1	41,3	64,2	42,6	24,9	21,6	39,3
9782	Active brownish grey clay, Pretoria	95,6	33,8	61,8	92,6	62,3	32,0	30,3	30,3
10499	Weathered granite, Stellenbosch	34,3	22,9	11,4	42,0	27,5	21,5	14,5	27,5
10500	Weathered granite, Stellenbosch	48,3	36,1	12,2	58,5	38,5	32,0	20,0	26,5
10501	Calcrete, Cape Flats	24,0	11,9	12,1	27,0	17,5	13,5	9,5	13,5
10502	Clay, Bloemfontein	61,9	24,9	37,0	68,5	44,0	28,5	24,5	40,0
10503	Shale and clay, Wesselsbron	36,7	15,7	21,0	43,5	25,8	16,5	15,0	27,0
10505	Dolomitic soil, Irene	72,7	47,6	25,1	83,0	58,5	42,5	24,5	41,5
10506	Talc schist, Halfway House	50,7	32,7	18,0	58,5	37,0	28,5	21,5	30,0
10507	Weathered shale, Pretoria	79,2	27,9	51,3	93,0	52,0	32,5	41,0	60,5
10508	Calcrete, Outjo, Namibia	65,7	46,5	19,2	80,5	45,5	29,0	35,0	51,5
10509	Calcrete, Malthöhe, Namibia	118,0	52,6	65,4	125,0	71,0	46,0	54,0	79,0
10510	Granitic soil, Okahandja, Namibia	27,7	14,2	13,5	30,5	19,5	13,5	11,0	17,0
10635	Blended reference soil (ex DOT)	22,7	14,1	8,6	28,0	20,0	14,0	8,0	14,0
10637	Blended reference soil (ex DOT)	31,5	15,1	16,4	36,0	24,5	16,0	12,5	20,0
10639	Garsfontein clay, Pretoria	46,9	23,2	23,7	56,0	33,5	22,0	22,5	34,0

Note: (1) Soil fines were oven dried at 105-110 °C at some stage before testing as part of the standard South African soil fines preparation method.

limits ± 5,4)

$$w_{20} = 1,01\ w_{LA} + 4,2 \quad (3)$$

(r = 0,986; n = 123; 9 laboratories; 95 % limits ± 5,4)

(ii) w_P with w_5

A good correlation was obtained between these two parameters:

$$w_P = 0,67\ w_5 + 0,8 \quad (4)$$

(r = 0,876; V = 21,3 %)

(iii) w_P with w_{MP}

The following linear regression was obtained:

$$w_P = 1,08\ w_{MP} - 1,1 \quad (5)$$

(r = 0,925; V = 16,8 %)

These results show that for all practical purposes, the Casagrande plastic limit is equal to (usually slightly less than) the minimum penetration moisture content. In other words, the soil has its highest shear strength at the plastic limit. This is in agreement with Campbell et al

(1980) who found that the minimum penetration moisture contents for 18 soils were always lower than the Casagrande plastic limit (between 3 % and 12 % wet weight). However, the very good correlation for 43 soils suggests that the minimum penetration moisture content should serve as a useful substitute for the w_P provided the precision limits are better.

(iv) I_P with I_{PC5} and I_{PCMP}

$$I_{PA} = 1,23\ I_{PC5} - 1,3 \qquad (6)$$

($r = 0,845$; $V = 36,7$ %)

$$I_{PB} = 1,35\ I_{PC5} + 4,3 \qquad (7)$$

($r = 0,928$; $V = 20,8$ %)

$$I_{PA} = 0,81\ I_{PCMP} - 0,3 \qquad (8)$$

($r = 0,818$; $V = 39,5$ %)

$$I_{PB} = 0,89\ I_{PCMP} + 3,2 \qquad (9)$$

($r = 0,900$; $V = 24,4$ %)

Whilst the I_{PC5} and I_{PCMP} are not numerically equal to I_P, the results show that a good correlation is obtained using I_{PC5}. The correlation with I_{PCMP} is not quite as good and the probable reason for this is that difficulty was experienced in identifying the minimum penetration moisture content, especially for soils of medium and high plasticity. This will be reflected in the precision limits presented later.

The use of fixed penetrations of 2 mm (Towner, 1973 - i.e. a 100-fold increase in shear strength from the w_{20} liquid limit) and 2,8 mm (Allbrook, 1980) and the moisture content corresponding to a 100-fold increase (Wroth and Wood, 1978) are considered impractical. Examination of the penetration moisture content curves indicates that a value of about 4 mm (i.e. a 25-fold increase in shear strength) is the minimum penetration that can be applied to all the soils tested, although a minimum of 2,8 mm (a 50-fold increase) can probably be applied in nearly all cases. In view of the problems of deriving accurate shear strengths from the penetration depths of a cone for all soils and because all soils do not possess the same shear strength at the liquid and plastic limits (Sampson, 1983), the choice of the actual depth to use as a replacement for the plastic limit is best decided by considerations other than shear strength. A value of 5 mm was chosen because it could probably be applied to all soils, it was found to correlate strongly with w_P and it showed better reproducibility than the other values tried (w_{10} and w_{MP}). As is the case with w_L and w_P, accurately defined, unique shear strengths for all soils probably cannot be assigned to w_{20} and w_P, only approximate average values.

REPRODUCIBILITY

Methods

Fourteen samples were all prepared as per the NITRR (1979) Method A1 and the oven-dried fraction passing 0,425 mm of each divided into sixteen subsamples. Nine subsamples were then selected at random and sent to the nine participating laboratories for determination of w_{LA}, w_P and I_{PA} by the NITRR (1979) methods and w_{20}, w_{10}, w_5 and w_{MP} by the extended BS cone penetration method. Eight of the laboratories used the one point Casagrande method and one the three point method.

In general the procedures specified in ASTM C670-77 (1980c) and the ancillary standards E177-71 and C802-77 were followed except that nine instead of ten laboratories, 14 instead of 5 materials and no instead of 4 replicates were used. The work has been reported in detail by Sampson (1983) and only the difference two-sigma (D2S) and D2S% limits are reported here (Table II). These terms provide a measure of the maximum acceptable difference between two test results by, in this case, two different laboratories, i.e. the multilaboratory or interlaboratory precision. The D2S limit is expressed in the normal test units and the D2S% limit as a percentage of the mean test result.

The American multilaboratory D2S limits are the same as the term 'reproducibility' of the British Standards Institute, for example in BS 812 Part 1:1975.

DISCUSSION

As has been shown by previous authors (e.g. Sherwood and Ryley, 1970; Weston, 1978; Karlsson, 1981) the reproducibility of the cone liquid limit method is superior to that of the cup method, although in this case the D2S% limit of 15 % for w_L is better than the 25 % reported by Weston (1978).

The I_{PA} has a mean D2S limit of 11 percentage units or a D2S% of 47 %. This means that, for the "average soil" tested, in 95 % of cases the results of two laboratories testing the same soil should not differ from each other by more than 11 units. In practice this limit is somewhat more accurately expressed as a D2S%, which means that the results of two laboratories should not differ from each other by more than 47 % of their mean value. For example, for a mean I_P of 8, the results could lie anywhere between 6 and 10, i.e. a D2S of 4 units in this case, not 11.

Table II shows that the reproducibility even in terms of D2S% limits varies considerably from soil to soil, e.g. from 21 to 77 % in the case of I_{PA}. For example, for the four soils with w_{LA}s of 23-32 these limits for I_{PA} vary from 41

TABLE II

D2S and D2S% limits from reproducibility study of the results of 9 laboratories

Sample Number	w_{LA} (mean of 9 labs)	D2S limits									
		w_{LA}	w_P	I_{PA}	w_{20}	w_{10}[1]	w_5[1]	w_{MP}[1]	I_{PC10}[1]	I_{PC5}[1]	I_{PCMP}[1]
10499	34	3,3	7,3	6,3	6,8	4,6	2,9	8,0	2,5	4,8	10,5
10500	48	4,1	7,2	6,2	7,7	5,9	3,8	11,8	3,9	5,0	9,1
10501	23	3,4	3,8	4,9	3,5	1,6	1,4	2,8	2,8	3,8	3,8
10502	62	12,3	12,6	10,9	10,9	10,9	8,4	15,3	4,5	5,5	18,1
10503	37	5,0	7,4	4,3	4,7	4,4	4,2	3,8	1,5	2,2	7,8
10505	73	6,9	16,0	12,3	7,1	8,1	8,0	14,1	7,9	10,3	13,8
10506	50	5,8	8,2	10,9	7,7	5,3	6,1	12,6	7,2	9,8	11,0
10507	80	12,6	22,3	21,4	16,4	11,8	8,0	16,1	5,7	12,3	14,2
10508	66	9,7	10,4	13,8	5,7	5,2	7,3	14,5	5,7	9,8	11,8
10509	108	25,0	28,0	37,8	21,2	14,1	9,1	19,1	9,6	16,8	23,8
10510	27	3,8	6,9	7,3	1,9	2,5	3,3	5,6	3,9	3,0	5,8
10635	24	4,1	4,2	5,6	3,4	3,0	3,7	6,3	2,4	3,5	5,6
10637	32	6,8	4,7	7,0	2,6	2,9	2,4	7,0	1,7	2,6	7,3
10639	46	4,6	6,3	6,9	5,0	5,0	4,3	6,3	3,2	3,8	8,5
Mean D2S		7,7	10,4	11,1	7,5	6,1	5,2	10,2	4,5	6,6	10,8

Sample Number	w_{LA} (mean of (9 labs)	D2S% limits									
		w_{LA}	w_P	I_{PA}	w_{20}	w_{10}[1]	w_5[1]	w_{MP}[1]	I_{PC10}[1]	I_{PC5}[1]	I_{PCMP}[1]
10499	34	9,9	35,8	47,4	16,3	13,8	10,7	39,4	30,1	33,3	49,0
10500	48	8,7	21,4	43,4	13,3	12,8	9,7	41,9	33,9	26,4	30,6
10501	23	14,9	30,5	49,8	12,9	7,4	7,9	21,6	48,0	39,4	26,9
10502	62	20,0	47,2	30,9	15,7	19,8	18,6	54,2	31,2	22,7	44,1
10503	37	13,6	45,7	20,8	10,8	12,2	15,1	23,0	16,9	13,9	29,1
10505	73	9,6	37,3	41,2	8,7	11,7	13,6	32,5	65,3	45,6	36,5
10506	50	11,7	25,5	61,1	13,2	11,3	16,1	51,0	59,5	47,3	32,4
10507	80	15,9	71,1	44,5	17,7	17,2	15,7	57,7	23,2	29,4	21,8
10508	66	14,8	25,0	57,0	7,2	8,8	16,1	48,2	29,4	29,1	24,3
10509	108	23,2	48,2	76,5	16,8	15,5	13,1	42,1	27,6	29,3	29,4
10510	27	13,8	45,2	62,0	6,1	9,8	16,1	38,3	66,6	27,9	35,0
10635	24	16,8	31,5	51,3	11,6	12,5	19,0	44,0	44,0	36,9	37,3
10637	32	21,2	31,5	41,1	7,1	9,8	10,1	42,9	22,1	19,5	32,2
10639	46	10,1	28,3	29,0	8,8	12,0	13,0	27,8	22,0	16,1	25,4
Mean D2S%		14,6	37,4	46,8	11,9	12,5	13,9	40,3	37,1	29,8	32,7

Notes: (1) Figures for sample no. 10500 are the D2S and D2S% limits for 8 laboratories.
(2) The soils were tested in the order given (10499 to 10639).

to 62 %, with the soil with the best reproducibility (lowest D2S%) having the highest w_{LA} (and I_{PA}), the opposite of what might be expected. Similarly, the best reproducibility for I_{PA} (21 %) is shown by a soil with w_{LA} of 37 and the worst (77 %) by a soil of w_{LA} 108, the highest tested.

The test causing the main variation is the plastic limit test which has an average D2S% limit of 37. When this is coupled with that of the liquid limit test (15 %), then it is hardly surprising that the reproducibility of the I_P is so poor. Unfortunately, the D2S limits of w_{20}, w_{MP} and I_{PCMP} are almost identical to those of the Casagrande tests, although the D2S% values of w_{20} and I_{PCMP} are better. Thus, although the minimum penetration was shown to be virtually equal to w_P, there seems little point in adopting this if the reproducibility is no better. However, the w_5 values have D2S and D2S% limits less than half those of w_P and w_{MP}. The D2S and D2S% limits for the cone penetration index obtained from the difference in w_{20} and w_5 (i.e. I_{PC5}) are much better than (about two-thirds of) that for the plasticity index.

The limits shown in Table II are for soils with liquid limit of 23 to 108. For soils with liquid limits less than 50 (about the maximum likely to be used in controlled layer works), the mean D2S and/or D2S% limits for w_5 and I_{PC5} are much better than (about half of) those of the w_P and I_{PA} and also the w_{MP} and I_{PCMP} (Table III).

It is also likely that these precision limits will improve still further with continued experience of the cone penetration method, as in five of the nine laboratories it was a largely untried method (Fig.2). (All soils were tested in the same order, i.e. from 1 to 14.)

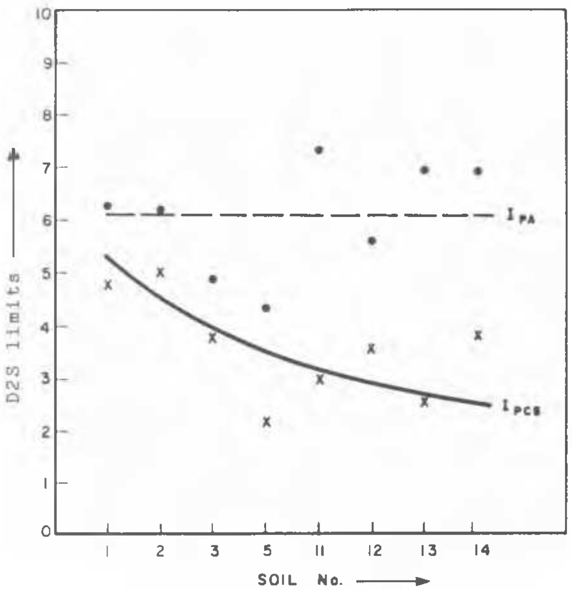

Fig.2 D2S of I_{PC5} and Casagrande I_{PA} compared for soils with LL < 50

An additional advantage of the I_{PC5} method is that the two parameters may be obtained in the same length of time it takes to obtain the liquid limit by the BS cone method at present. Four points have proved sufficient to obtain the straight line or curve between 5 mm and 20 mm penetrations. It is recommended that penetrations are obtained between 5 and 10 mm, 10 and 15 mm, 15 and 20 mm and 20 and 25 mm, and taken from the drier to the wetter state. For soils of low plasticity, a straight line is likely to be obtained with the 5 mm penetration point being the limit of the linear portion. For soils of medium and high plasticity, a concave curve is obtained and it is important to draw the curve through the points and not to take the straight line fit of the points.

It is necessary to use the two moisture contents (w_{20} and w_5), as the slope of the penetration versus moisture content curve varies for different soils. Just as it is possible to have a soil with the same w_L but a different I_P (i.e. different flow index), so it is possible to have the same w_{20} but different I_{PC5} (i.e. different consistency index).

To summarise, the results of the reproducibility investigation show that the I_{PC} taken as the difference between the 20 mm (w_{20}) and the 5 mm (w_5) penetration moisture content has sufficiently superior limits (about half of those of the I_P) to warrant its adoption as a replacement for the latter. The 5 mm penetration moisture content (w_5) should also be used as a replacement for the plastic limit. For the design and control of layer works it is suggested that the maximum desirable D2S% for w_L or w_{20} is about 10 % and that for I_P or I_{PC} about 25 %. With practice it is felt that these limits can be achieved on most soils only by means of the cone method.

ADVANTAGES AND DISADVANTAGES OF EXTENDED CONE PENETROMETER METHOD

The advantages of replacing the cup liquid limit method with that of the BS cone, as summarised by Sampson and Netterberg (1984), are that it is more repeatable, more reproducible, not operator-susceptible, less prone to equipment variations, and that it is capable of giving results for materials which slide in the conventional cup, such as soils of low plasticity and micaceous (Kumapley and Boakye, 1980) soils. The advantages of replacing the I_P with the I_{PC} are similar. In addition, the method gives results on soils which slide in the normal cup comparable to those yielded by a roughened cup (Kumapley and Boakye, 1980), and should therefore give reliable results on soil-aggregate basecourses of low plasticity on which bar linear shrinkage tests are currently considered to be advisable. These tests can therefore probably be discontinued. A further advantage is that the time taken to determine the w_{20} and the I_{PC} is less than that required for the w_L and the I_P.

As no international standard (ISO) test methods for soils have so far been accepted, the adoption of these new indices as international standards would overcome the problems of which Atterberg limit method to adopt.

The disadvantages of adopting the extended cone method (Sampson and Netterberg, 1984) are that a greater quantity of soil fines must be prepared, that care is required in filling the cup and striking it off level, that care is required in handling the cone, and that it may wear. These disadvantages are considered insignificant, as shown by the greater repeatability, reproducibility and non-operator susceptibility of the test, and are easily overcome. The only significant disadvantages of the method appear to be the greater cost of the cone tester, the necessity for the modification of soil specifications, etc. and the retraining of staff. There is also the possibility of errors due to confusing the two sets of indices.

TABLE III

Mean D2S and D2S% limits for eight soils with liquid limits < 50

	w_{LA}	w_P	I_{PA}	w_{20}	w_{10}	w_5	w_{MP}	I_{PC10}	I_{PC5}	I_{PCMP}
Mean D2S	4,4	6,0	6,1	4,4	3,7	3,2	6,4	2,7	3,6	7,3
Mean D2S%	13,6	33,7	43,1	10,9	11,3	12,7	34,9	35,5	26,7	33,6

Note: (1) The mean for 8 laboratories for sample 10500 from Table II was used for these values.

However, it is believed that the advantages of the extended cone method far outweigh its disadvantages and that it has considerable potential as an international standard method for replacement of the liquid and plastic limits and plasticity index if further studies by other organisations on other soils support it.

SOME IMPLICATIONS OF ADOPTING THE EXTENDED CONE PENETRATION METHOD

As both w_{20} and I_{PC} differ from the ASTM w_L and both the ASTM and BS I_Ps respectively, the implication of adopting the former two indices are too numerous to be described here in detail. In general, however, they are obvious. For example, in the case of countries employing the ASTM liquid limit device, the common maximum w_{LA} requirement of 25 for basecourse would, from equation 3, have to be changed to 29. However, from equation 6 the usual I_{PA} requirement of 6 would remain numerically unchanged at an I_{PC} of 6,t he reason being that whilst w_{20} is approximately 4 units higher than w_{LA}, w_5 is also higher than w_P by the same order.

In the case of countries employing a BS device (whether cone or cup), the equivalent limits would remain numerically unchanged at 25 for w_{20}, as this equals the BSw_L. However, from equation 7, an I_{PB} of 6 would give an equivalent maximum I_{PC} requirement of 1, which is probably too low for control purposes. The low I_{PC} is merely a reflection of the more conservative requirements obtained using the British Casagrande device, which yields a w_{LB} and an I_{PB} of 4 units higher. It is insufficiently appreciated that specifying an I_{PB} of 6 is equivalent to an I_{PA} of 2.

Similarly, all other specifications, soil classifications and equations relating to soil properties and behaviour in terms of w_L and I_P would also have to be converted. However, adoption of the cone parameters internationally may serve to standardise specified limits internationally, thus alleviating some of the confusion which exists using the present methods and limits.

CONCLUSIONS

1. The mean interlaboratory precision (reproducibility) of the w_L, w_P and I_P for 14 soils tested by 9 laboratories and expressed in terms of D2S% limits (15, 38 and 47 % respectively) are unsatisfactory for the design and quality control of layer works. These figures cannot be expected to improve significantly with further experience and modification of the tests.

2. The moisture content at a penetration depth of 20 mm in the BS cone liquid limit method (i.e. BSw_L) is very strongly correlated with (r = 0,99) and has a superior reproducibility to the ASTM cup liquid limit (w_L). It is therefore suggested that the BSw_L determined using the BS cone penetrometer method should replace the existing liquid limit determined using an ASTM cup device. For all practical purposes the BSw_L (and therefore also the BSI_P) are 4 units higher over the range 20 to 100.

3. Whilst it was found that the plastic limit and the minimum penetration moisture content (i.e. that corresponding to the maximum undrained shear strength) were both strongly correlated and numerically almost equal, the reproducibility of the latter was no better. It is therefore recommended that this is not used as a replacement for the existing plastic limit.

4. The moisture content at a cone penetration depth of 5 mm is both strongly correlated with (though not numerically equal to) and has a superior reproducibility to (about half of) that of the plastic limit and is therefore suggested as a replacement for the plastic limit.

5. The cone penetration index is both strongly correlated with (though not numerically equal to) and has a superior reproducibility to (almost half of) that of the plasticity index and is therefore suggested as a replacement for it.

6. With further practice and experience the reproducibility of the cone penetration index can probably be improved to better

than a D2S% of 25, while little further improvement is forseen in the case of the plasticity index.

7. There is no international standard method for the determination of Atterberg limits and national standards differ significantly from each other. The reproducibility on an international scale of the Atterberg limits is therefore probably worse than that the figures presented here.

8. The extended BS cone penetrometer method for the determination of the moisture contents at penetration depths of 20 and 5 mm and for the cone penetration index should be considered for an international (ISO) standard to replace the liquid and plastic limits and the plasticity index, respectively. Although specifications, soil classifications and formulae relating soil properties and behaviour to these index properties would have to be rewritten, the long-term benefits are considered to outweigh these disadvantages.

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