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An accurate, quick and simple method to determine the plastic limit and consistency changes in all types of clay and soil: The thread bending test

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ABSTRACT

The standard thread rolling method for determining the plastic limit of soil, PL, has been widely criticized for requiring considerable judgment from the operator that carries out the test. In different studies other methods have been put forward; however, these methods cannot compete with the thread rolling test in simplicity, execution time and cost.

In this article an accurate, quick and simple method is presented with a simple device for determining the plastic limit of soils, in which the subjective point of view of the operator is omitted. Soil threads which are 3 mm in diameter and 52 mm long are bent until they start to crack. The relationship between the bending produced, B, and water content, W, has been studied, in such a way that the plastic limit, PL, and another two new parameters (the stiff-soft limit, SSL, and the bend-breaking limit, BL) have been determined with minimal operator interference. These new parameters delimit other consistency states, which may be very useful in sectors such as the ceramics industry, agriculture or geotechnical engineering.

The PL results obtained by the bending test in 24 soils concur to a great degree with those obtained in the thread rolling test by a highly experienced operator ($R^2 = 0.972$). Moreover, these results have been endorsed by Shapiro–Wilk and Student's T statistics tests. Finally, the reliability of the method using only 3 and 1 experimental points has been studied too which have yielded very similar results to those obtained with 6 and 7 points.

1. Introduction

Atterberg in 1911 defined seven consistency limits for fine-grained soils, of which the liquid limit, LL, and the plastic limit, PL, are the most important, since they mark the boundary between liquid and plastic states, and between plastic and semisolid states, respectively.

LL determination is carried out mechanically, dispensing with the operator judgment, according to several standards around the world based on the Casagrande method (e.g. UNE 103-103-94; ASTM D 4318–05) or the penetration test (BS, 1377–2:1990). By contrast, the most popular and standardized method for PL determination, the so called "thread rolling test" is based on rolling soil into 3 mm threads by hand until the operator considers the soil to be crumbling (e.g. UNE 103-104-93; ASTM D 4318–05). Therefore, the skill and judgment of the operator play a critical role in the outcome of the test. Many factors are not controlled, such as the pressure applied, the contact geometry and the friction or the speed of rolling (Whyte, 1982), as well as the size of the sample and the type of soil. These last two factors are the main ones that affect the final result (Temyingyong et al., 2002).

The international soil classification system (the Casagrande Chart) shown in ASTM D, 2487–00, based on the work of Casagrande (1932, 1948) is a very useful tool for determining the plastic and geotechnical properties of soils. Errors in the PL imply that the soil has been incorrectly identified and classified (Sokurov et al., 2011). As a consequence of this, this classification system sometimes appears unreliable, so it has been the object of a great deal of criticism which has caused it to be revised (Gutiérrez, 2006) and even to new proposals for classification (Polidori, 2003, 2007, 2009), while the underlying problem, PL determination, remains unsolved.

A review of the different methods to measure soil plasticity has been presented by Andrade et al. (2011) including the Pfefferkorn test, penetration methods, capillary rheometer, torque rheometer or stress–strain curves. Baran et al. (2001) adapted a stress-deformation test for metals to study the plastic properties of clays but this mainly focused on their workability, and the issue of considering an alternative method for determining the plastic limit was not tackled. With the special instance of cone penetration tests, a great deal of research has gone into defining a new methodology for PL determination without reaching any real agreement; for example: Wroth and Wood (1978) were in favor of obtaining the PL through the fall cone test, based on the misconception that the shear strength at the PL is 100 times that at the LL; from this same idea, Harison (1988) used a semi-logarithmic model to determine the PL as the water content corresponding to a penetration value of

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2 mm; by contrast, Feng (2000) applied a linear model based on a double logarithmic scale and used a ring to prepare the soil specimens (the design of this ring was improved in Feng (2004)); Lee and Freeman (2009) determined simultaneously the LL and PL with a dual-weight fall cone and Sivakumar et al. (2009) attached a cylinder and piston to the usual cone apparatus in order to increase the load by air pressure and to obtain the PL at a penetration depth of 20 mm. However, all of it is based on the assumption that the plastic limit corresponds to a defined shear strength, which is not correct (Haigh et al., 2013).

In other more recent works, such as those described by Barnes (2009, 2013) the rolling conditions of soil cylinders were emulated, in which stresses and strains and even soil workability were measured and in which other less well-known consistency limits could be obtained. In principle, the Barnes method appears to work, although some shortcomings have been identified with this approach: many experimental points and extensive data processing are required (which increases complexity and test time). Furthermore, a relatively complex apparatus is necessary (which increases cost and complexity). Additionally, the main issue, that is, the means of obtaining the PL is questionable, since this is done by an arithmetic mean between two points (one on each side of the PL) and strictly speaking, the PL does not have to be the average in that range, but could be any moisture value included in it. Therefore, so as to curtail the importance of this, the Barnes method requires the moisture values on either side of the PL to be very similar which undoubtedly would lead to an increase in the time and difficulty of the test.

Apart from the inherent weaknesses of the methods described above, not all of them are viewed as being possible alternatives to the thread rolling test, since they cannot compete against it in terms of simplicity, execution time and cost. This must be why the thread rolling method continues to be the most widely used test for PL determination.

In this article, a new and simple method is presented. The thread bending test (or simply bending test) allows not only the PL, but also other parameters related to soil consistency to be obtained accurately, so a real and practical alternative is offered to the traditional method.

2. Materials and methods

2.1. Sampling and initial preparation of test samples

Twenty four soil samples were collected from different geological locations throughout the province of Toledo (central Spain). This way samples presented different grain-sizes and compositional characteristics (Table 1), so a good representativeness of different types of soil was obtained. All samples were stored in polyethylene bags and then they were reduced by quartering to keep the original representativeness and homogeneity.

The soil was dried in an oven at a temperature of 55 °C. Subsequently, it was disaggregated manually by a mortar and rubber covered pestle and passed through a 0.40 mm sieve. Fractions of under 0.40 mm were used in the tests.

2.2. Mineralogical study, particle size distribution and Atterberg limits by standard methods

The mineralogical study of the soil samples was carried out by means of X-ray diffraction (XRD) analysis. The clay mineralogy was determined in oriented aggregates (OA) of the <2 mm fraction obtained by sedimentation from an aqueous suspension onto glass slides and were examined on a PANalytical® diffractometer, X'Pert Pro model. The conditions used were: 45 Kv, 40 mA, CuKα radiation and a system of slits (soller–mask–divergence–antiscatter) of 0.04 rad–10 mm–1/8°–1/4° with an X'celerator detector. The OA were subjected to thermal treatment at 550 °C for 2 h and to solvation with ethylene glycol at 60 °C for 48 h.

Particle size distribution of soils was determined according to ASTM D 422–63 (1998). Fractions above 63 μm were determined by sieving and the silt-clay fraction by sedimentation with a 152H (ASTM E 100–05) Bouyoucos hydrometer. From the grain size distribution data, soils were classified according to the internationally accepted Soil Texture Triangle (USDA, 1993).

For determining the Atterberg limits, soils were previously amassed with distilled water. The amount of added water was that necessary to provide a soil consistency that would require about 25 to 35 blows in the LL test, as well as that at which the soil can be rolled without sticking to the hands for the PL test. Each homogeneous soil–water mixture was stored for 24 h under hermetic conditions in polyethylene bags, thereby, preserving their initial moisture content. The liquid limit, LL, and plastic limit, PL, were determined by the Casagrande method and the thread rolling test in accordance with the UNE 103-103-94 and UNE 103-104-93 standards, respectively and homologous to the ASTM D 4318–05 standard.

Table 1
Soil sources and general description. Sm: smectite, Ill: illite, Kao: kaolinite, Chl: chlorite, ML: mixed layer clay minerals.

Soil name	Location or source	General description	Sampling depth	Clay mineralogy
M1	Valdehierro Valley — Madridejos	Brownish-gray descomposed granite (artificially material pile)	0–50 cm (material pile)	Sm, Ill, Kao
M2	Valdehierro Valley — Madridejos	Dark-brown sandy silt (sedimentary deposits on a stream bank)	0–20 cm	Ill, Kao
M3	Valdehierro Valley — Madridejos	Dark-brown silt (sedimentary deposits on a stream bank)	20–30 cm	Ill, Kao
M4	Urda area — private company	Commercial brownish gray artificial graded aggregate	0–50 cm (material pile)	Sm, Ill, Chl, Kao, ML
M5	La Sagra area — Pantoja	Brown clay	120–140 cm	Ill, Kao, Sm
M6	Valdehierro Valley — Madridejos	Mustard-colored clay with pebbles and gravel	30–40 cm	Ill, Kao, Sm, ML
M7	Madridejos — agricultural soil	Red clay	2–20 cm	Ill, Kao, ML
M8	La Sagra area — Borox	Highly calcareous light-gray silty clay	100–120 cm	Sm, Ill
M9	La Sagra area — Borox	Greenish sandy clay	100–120 cm	Sm, Ill, Kao, ML
M10	Tembleque — agricultural soil	Calcareous brown clay	2–20 cm	Ill, Kao, Chl, Sm, ML
M11	La Sagra area — Pantoja	Brown sandy soil	140–160 cm	Ill, Kao, Chl, Sm, ML
M12	La Sagra area — Pantoja	Highly plastic brown clay	200–220 cm	Ill, Kao, Chl, ML
M13	La Sagra area private company	Commercial light-brown bentonite	0–50 cm (material pile)	Sm, Ill, Kao
M14	Southwestern Toledo	Highly descomposed brownish granite	20–40 cm	Ill, Sm, Kao
M15	Valdehierro Valley — Madridejos	Dark-brown silt (sedimentary deposits on a stream bank)	0–20 cm	Ill, Chl, Kao
M16	Madridejos — agricultural soil	Brown silty clay	2–20 cm	Ill, Kao, ML
M17	Valdehierro Valley — Madridejos	Red clay	30–40 cm	Sm, Kao, Ill, ML
M18	Madridejos — agricultural soil	Orange clay	2–20 cm	Ill, Kao, ML
M19	Valdehierro Valley — Madridejos	Brown silt	20–30 cm	Ill, Kao, ML
M20	Madridejos city	Brown silt with gypsum (building waste)	0–30 cm	Ill, Kao, Sm, ML
M21	Villarrubia de Santiago	Calcareous beige silt	20–40 cm	Ill, Kao, ML
M22	Mixture	15% M12 + 85% M16	See M12 and M16	Ill, Kao, ML
M23	Mixture	15% M13 + 85% M16	See M13 and M16	Sm, Ill, Kao
M24	Almonacid de Toledo area — private company	Commercial gray artificial graded aggregate	0–50 cm (material pile)	Sm, Ill, Kao

Both methods were carried out by a highly experienced operator (with a record of having carried out over 4000 plasticity tests) to ensure that the tests were properly carried out and thus to compare sound PL thread rolling results with those obtained by the method proposed in this study.

2.3. The thread bending test

Just as with the LL and PL standard test, soils were homogeneously amassed with distilled water. In this case, 3 to 5 different soil moisture balls were prepared. Each soil–water ball of 30–40 g approx. was stored for 24 h under hermetic conditions in polyethylene bags.

After this tempering period, each ball of soil was tested as follows:

The soil ball was flattened on a nonabsorbent smooth glass plate. The flattening was performed by hand (preferably using latex gloves to prevent loss of soil moisture) until the thickness was slightly higher than 3 mm; at this point, an aluminum tool designed in this research called the thread molder (Fig. 1a, b, c and Fig. 2) was used to obtain a thickness of exactly 3 mm (the thread molder is described in more detailed below).

The jagged edges of the soil mass were cut with a metal spatula after which a strip that was at least 52 mm long and a square section of approximately 3 × 3 mm was cut. From this strip, a cylindrical thread with a diameter of exactly 3 mm which was 52 mm long was shaped by the thread molder: the thread molder (Fig. 1a) is designed in such a way that there is a space of exactly 3 mm between the part which shapes the soil thread and the glass plate. The thread molder was successively moved backwards and forwards by hand until the exact moment at which the initially square section of the soil thread became round (Fig. 2a). The 3 mm round section thread was cut with a metal spatula for which the width of the thread molder was employed as a template (it measures 52 mm wide) in order for it to measure 52 mm in length. Then, on the same glass plate, the soil thread was bent according to Fig. 2b and Fig. 3a, b. To do so, the steel pushers designed (Fig. 1d, e and Fig. 2b) were used as mobile supporting points and a cylindrical part of the thread molder worked as a fixed supporting point. Bending was stopped at the point of cracking. Right afterwards, the distance between the tips of the thread was measured with a caliper and recorded to a precision of 0.1 mm. This measurement was taken from the central part of the tips (Fig. 3c). When the soil is very wet, deflections can be so large that even the thread tips come into contact (Fig. 3d). In this case, the soil thread was bent by hand (the pushers and thread molder were not necessary) until the point of cracking as is shown schematically in Fig. 3e. The distance between the thread tips was taken as shown in Fig. 3f and Fig. 4, but here the value was recorded with a negative sign.

All these steps were repeated for at least two other soil threads. Alternatively other cylinders were shaped exactly like those that were bent, but their tips were not cut since they were simply used to obtain enough material to correctly determine their moisture content (a minimum of 5 g is recommended). The material was put into a container whose weight was known and was weighed to a precision of 0.01 g. It

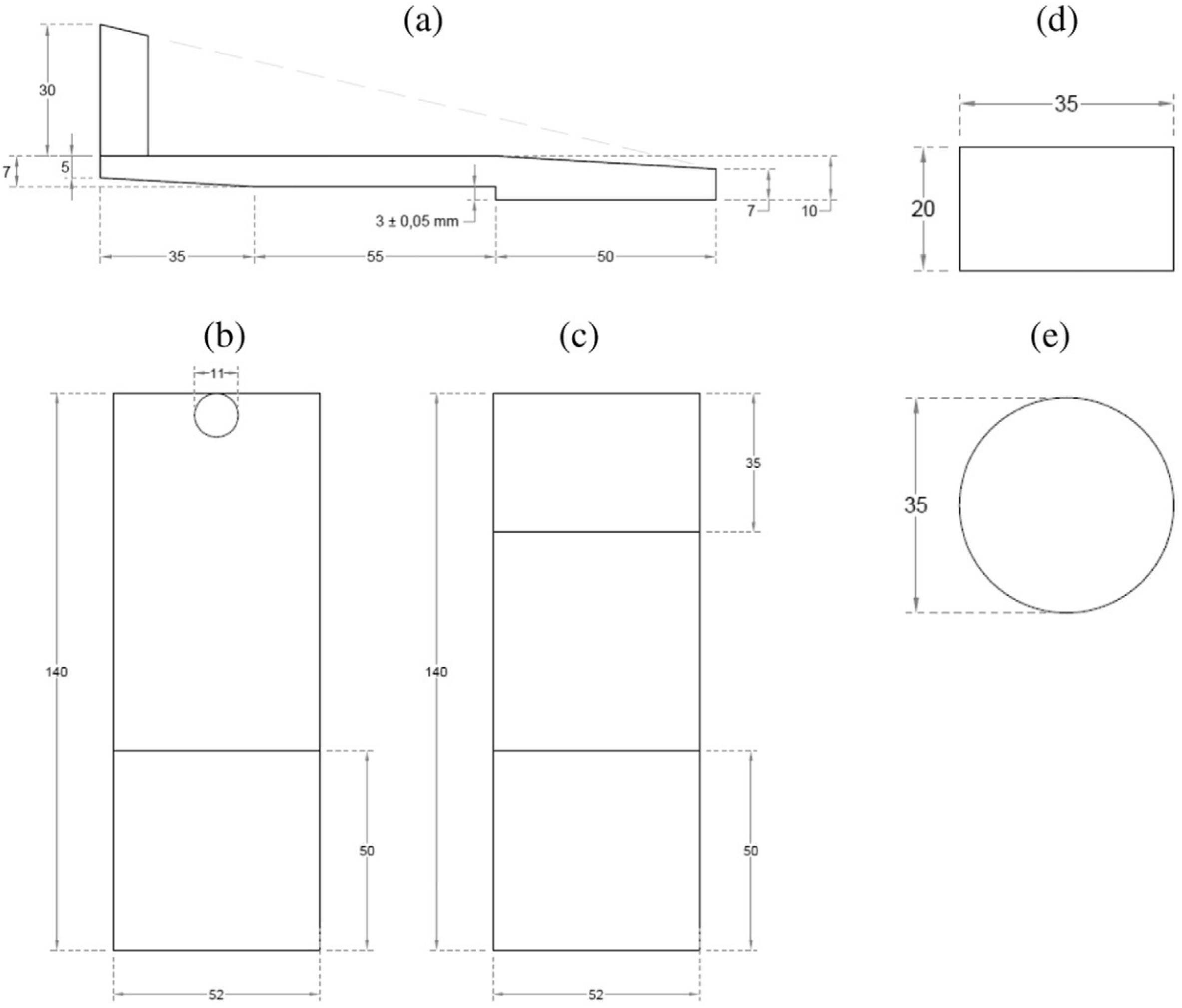

Fig. 1. Drawings and dimensions in mm of the thread molder and the steel pushers. (a) Side view, (b) top view and (c) bottom view of the thread molder; (d) front view and (e) top view of the steel pushers.

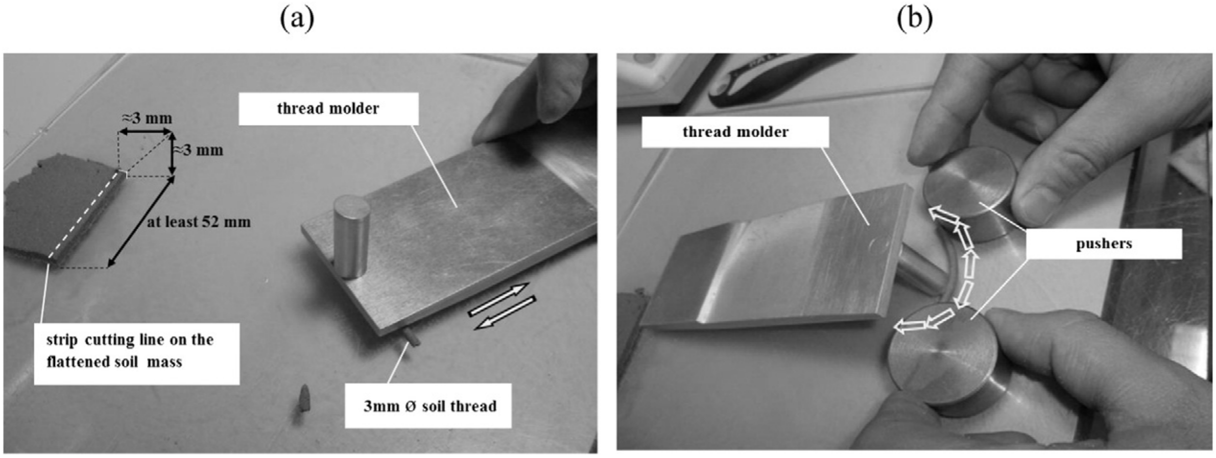

Fig. 2. (a) Shaping of a soil thread with the thread molder and size of the soil strip to be cut. (b) Bending of a soil thread; the arrows indicate the bending technique.

was dried in an oven for a minimum of 24 h at 105 °C until its weight was constant in order to determine its moisture content (W).

This whole process was repeated with the other soil balls that had been prepared earlier. Different moisture contents were also obtained by mixing balls or by hand drying, so between 3 and 7 experimental points were obtained.

3. Results and discussion

3.1. Mineralogical study, particle size distribution and Atterberg limits according to standardized methods

As can be seen in Table 2, there are a wide range of soils in terms of plastic and particle-size properties. According to the USDA texture classification (1993) there are sandy, silty, clayey and intermediate-grained soils in this study. Likewise, the Atterberg limits results and Casagrande classification show soils with very low (M4 and M21), low (M2, M6, M11, M14, M15, M16, M19 and M24), medium (M1, M3, M7, M10, M17, M18, M20 and M22), medium-high (M5 and M23), high (M8, M9 and M12) and very high plasticity (M13). Another property that is also shown is the so called activity, A, introduced by Skempton in 1953 as the ratio of plasticity index (PI = LL–PL) to <2 μm clay fraction. Despite the fact that the Skempton activity index is unable to show accurate mineralogical results, it is a sound indicator, in general terms, of the type of clay contained in soil which influences the Atterberg limits (Schmitz et al., 2004). For example, typical A values are: 1.25 to 7 for smectite (active clays), 0.75 to 1.25 for illite (normal clays) and less than 0.75 for kaolinite (inactive clays). In this regard, a wide variety of Skempton activity data can be observed: active soils (M8, M13), normal soils (M9, M23) and inactive soils (the remaining samples), which shows that the tested soils have different chemical and mineralogical compositions. This last aspect is ratified in Table 1, where it is observed a wide representativeness of clay minerals, with a significant presence of smectite, illite, kaolinite, chlorite and mixed-layer clay minerals, which vary depending on the soil sample.

Taking into account the wide heterogeneity of the samples, in principle, the results and conclusions of this research could be applied to any type of soil, whatever its properties are.

3.2. Initial data processing

A new parameter called *bending at cracking* or simply *bending*, B, was devised to ascertain the extent of bending that the cylindrical soil threads were subject to for each moisture content:

$$B = 52.0 - D \qquad (1)$$

where, D is the average distance measured between the tips at the time of cracking and 52.0 refers to the length in mm of the soil thread.

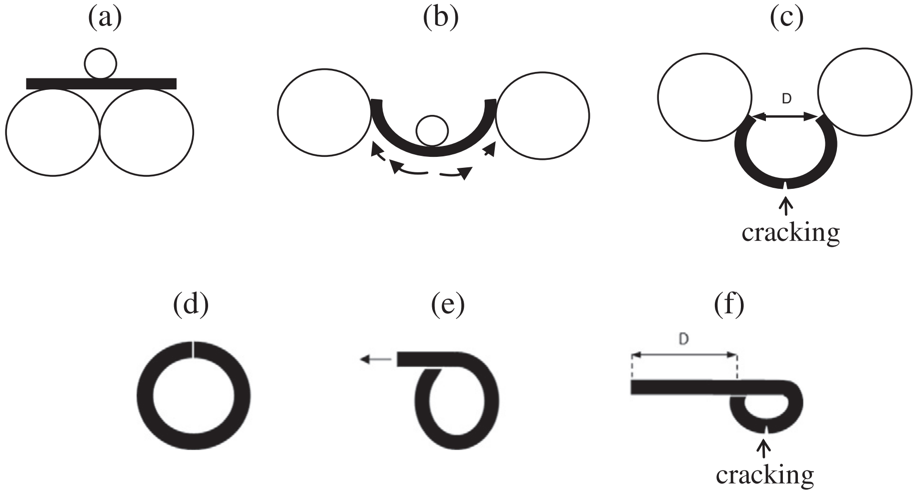

Fig. 3. Schematic drawing where bending and tip distance measurement techniques are detailed. (a) Initial position. (b) Usual bending technique and (c) usual measurement technique of a cracked thread. (d) Soil thread in which tips come into contact and can form a closed ring. (e) Bending technique to be followed when the soil thread is able to bend beyond a closed ring and (f) the measurement technique for this last case.

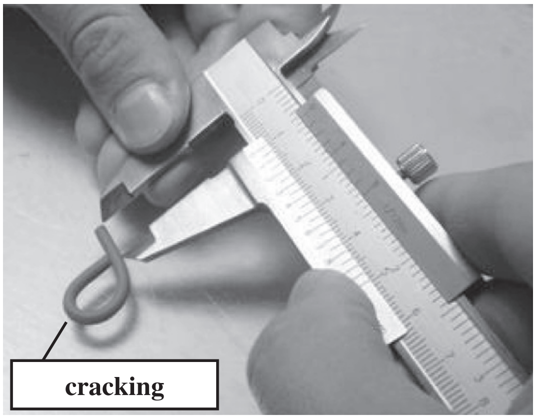

Fig. 4. Tip distance measurement of a very flexible thread with a caliper just after cracking.

Bending values, B, obtained from Eq. (1) were plotted against water content, W. Between 3 and 7 B–W experimental points were obtained for each soil (Fig. 5). In all cases, the correlation of the points can be defined in two ways, without compromising in any way the correct definition of the point path: as a parabolic curve (Fig. 6a) or as two intersecting lines (Fig. 6b).

The parabolic curve was named the bending curve (Fig. 6a) whose equation is:

$$W = z \cdot (B^{m}) \tag{2}$$

where z is a constant, *m* is the so called *bending slope* that is the value of the straight line slope formed when the bending curve is represented in double logarithmic scale. All other terms were defined previously.

As noted above, the arrangement of the points may also be defined by two straight lines with different slopes which intersect at an intermediate point (Fig. 6b). This cutoff point corresponds to a moisture content at which a change of consistency occurs. Despite the fact that the thread bending test does not measure stresses, a stiff-plastic consistency has been observed in the water contents corresponding to the steepest line, whereas the consistency state in the less steep line was viewed as being soft-plastic. As water works as a lubricant between the clay sheets, the stiffer the soil, the more water will be needed to deform it (here deformation is by bending). This makes sense, since a steeper slope indicates that more water is required to bend the thread soil because of its stiffness, while a gentler slope indicates that the soil thread does not need a lot of water to bend easily, since this is in a softer state. In fact, the shape of the graphs obtained by the thread bending test, like the one shown in Fig. 6b, are very similar to others obtained by much more complex stress–strain tests, e.g. those obtained by Barnes (2009, 2013) and even the same consistency states have been perceived.

Therefore, the steepest line corresponds to lower B values and moisture contents in which the soil has a stiff-plastic consistency, hence its name, the stiff-plastic line which is defined by the following equation:

$$W = j_{stiff} \cdot B + c_{stiff} \tag{3}$$

where, j_{stiff} is the value of the stiff-plastic line slope and c_{stiff} is a constant that corresponds to the cutoff point of the stiff-plastic line with the y-axis.

Conversely, the gentler line defines the range of moisture in which the soil is soft-plastic and workable, without actually being really sticky. This second line is called the soft-plastic line and is defined as:

$$W = j_{soft} \cdot B + c_{soft} \tag{4}$$

where, j_{sosft} is the value of the soft-plastic line slope and c_{soft} is a constant that corresponds to the cutoff point of the soft-plastic line with the y-axis.

Being able to describe the point path both as a parabolic curve and as two straight lines is, as will be seen later, a very useful tool to define changes in soil consistency, without obtaining a large number of experimental points.

Table 2

Percentages of clay, silt and sand and USDA texture classification according to the grain size distribution. Results of LL, PL and PI according to UNE 103-103-94 and UNE 103-104-93 standards and Casagrande plasticity classification. Skempton activity (A) of each soil sample is shown in the last column.

Soil	% clay (<2 μm)	% silt (2–63 μm)	% sand (>63 μm)	USDA texture classification	LL	PL	PI (LL–PL)	Casagrande classification[a]	Activity (PI/% < 2 μm)
M1	19.92	18.60	61.48	Sandy loam	33.8	19.3	14.5	CL	0.73
M2	16.49	36.24	47.27	Loam	26.9	18.8	8.1	CL	0.49
M3	18.03	62.89	19.08	Silt loam	31.8	21.0	10.8	CL	0.60
M4	12.39	49.03	38.58	Loam	16.3	12.5	3.8	ML	0.31
M5	57.29	26.64	16.07	Clay	49.4	21.0	28.4	CL/CH	0.50
M6	33.05	27.86	39.09	Clay loam	28.0	13.2	14.8	CL	0.45
M7	44.88	30.76	24.37	Clay	35.1	14.6	20.5	CL	0.46
M8	18.50	68.45	13.05	Silt loam	83.3	30.1	53.2	CH	2.88
M9	25.63	27.32	47.05	Sandy clay loam	80.0	49.7	30.3	MH	1.18
M10	33.57	49.38	17.05	Silty clay loam	34.9	20.0	14.9	CL	0.44
M11	20.58	10.37	69.05	Sandy clay loam	22.8	12.9	9.9	CL	0.48
M12	66.47	31.16	2.38	Clay	62.5	28.1	34.4	CH	0.52
M13	67.79	26.06	6.15	Clay	214.4	37.1	177.3	CH	2.62
M14	19.44	16.43	64.12	Sandy loam	29.5	20.0	9.5	CL	0.49
M15	14.31	51.45	34.23	Silt loam	21.9	16.2	5.7	CL–ML	0.40
M16	31.01	46.38	22.61	Clay loam	26.2	16.0	10.2	CL	0.33
M17	36.87	46.23	16.89	Silty clay loam	36.9	17.1	19.8	CL	0.54
M18	41.89	26.38	31.73	Clay	30.3	14.9	15.4	CL	0.37
M19	19.48	52.79	27.72	Silt loam	22.0	13.7	8.3	CL	0.43
M20	20.88	48.71	30.41	Loam	33.1	17.9	15.2	CL	0.73
M21	13.30	48.34	38.36	Loam	14.3	13.7	0.6	ML	0.05
M22	35.37	44.56	20.07	Clay loam	31.6	16.0	15.6	CL	0.44
M23	34.77	45.00	20.24	Clay loam	48.7	17.0	31.7	CL	0.91
M24	20.97	28.98	50.05	Loam	26.2	15.6	10.6	CL	0.51

[a] Classification system shown in the standard ASTM D 2487–00.

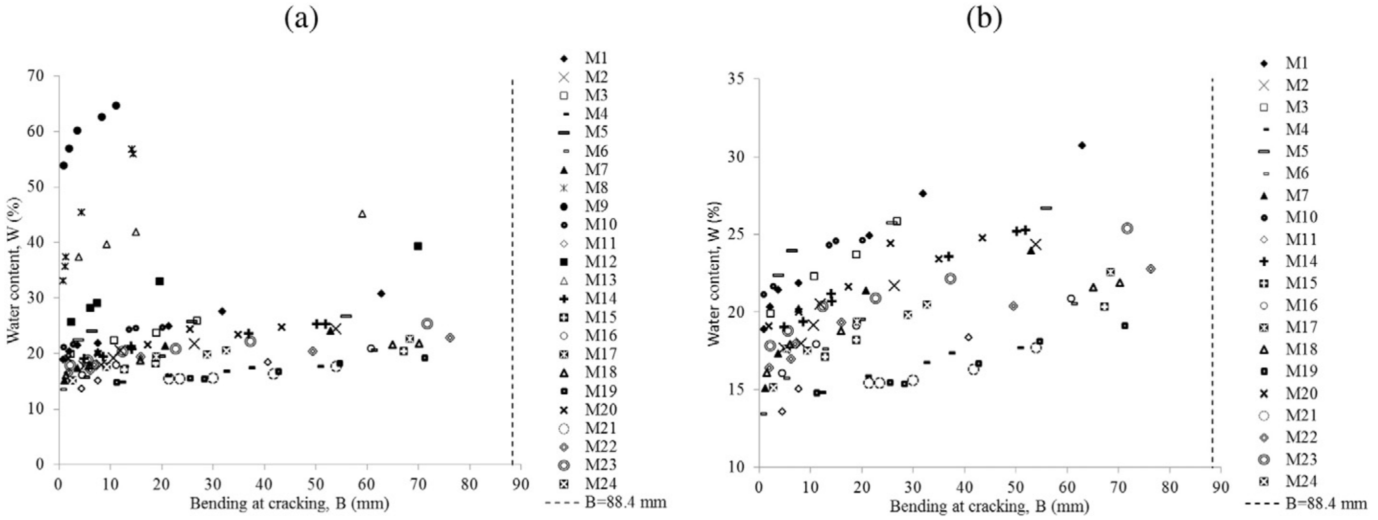

Fig. 5. (a) Experimental points obtained from the thread bending test for all the tested soils. (b) More detailed view for samples with water contents below 35%.

3.3. Parameters obtained from the thread bending test

Considering the above, the stiff-plastic and soft-plastic lines are useful tools to establish the limits between different consistency states from the following parameters:

Plastic limit, PL: Strictly speaking, the plastic limit corresponds to a moisture content at which the soil is no longer able to resist deformation, and so it breaks immediately when attempts are made to deform it. The PL for the bending test is based on this and is obtained as the moisture content that corresponds to a bending of B = 0 mm, so that, the soil is not capable of withstanding deformations below this threshold (nonplastic state) but it does bear them above it (plastic state). Therefore, the PL is the moisture percentage corresponding to the cutoff point of the stiff-plastic line with the y-axis, that is:

$$\mathrm{PL} = c_{\mathrm{stiff}} \tag{5}$$

Bend-breaking limit, BL: This is a new parameter obtained from the soft-plastic line as the moisture content, W, corresponding to B = 88.4 mm. This is the threshold value above which the soil thread is soft enough to bend completely without breaking. Thus, the soils mostly have a quite soft and sticky consistency when their moisture contents are close to the BL.

$$\mathrm{BL} = j_{\mathrm{soft}} \cdot 88.4 + c_{\mathrm{soft}} \tag{6}$$

B value = 88.4 was obtained according to Fig. 7. It was considered that the cylindrical soil thread forms a circumference with radius, r, equal to 3 mm in the bending area.

In this way, D_{BL} and B_{BL} were obtained as follows:

$$D_{\mathrm{BL}} = -(52.0\text{–}((3/4 \cdot \text{circumference perimeter}) + (r/2))) \tag{7}$$

where D_{BL} is the distance between the thread tips for the BL moisture content, whose result is $D_{BL} = -36.36$ mm and r is the radius equal to 3 mm.

Thus, according to Eq. (1): $B_{BL} = 52-(-36.36) = 88.36$ mm i.e., $B_{BL} = 88.4$ mm where B_{BL} is the bending at cracking for a moisture content equal to BL (in this case cracking does not occur).

Because of the difficulty of handling a 3 mm soil thread at or above the BL water content (the consistency is sticky or too soft), the result of D = −36.36 (i.e., B = 88.4 mm) was experimentally verified using plasticine. The result obtained was the same as that calculated from Eq. (6) and Eq. (7).

Stiff-soft limit, SSL: The SSL is a new parameter defined as the moisture percentage corresponding to the intersection point of the stiff-plastic line with the soft-plastic line. SSL marks the transition point between stiff-plastic and soft-plastic consistency states and is determined from the stiff-plastic line equation or the soft-plastic line equation as:

$$\mathrm{SSL} = j \cdot B_{\mathrm{SS}} + c \tag{8}$$

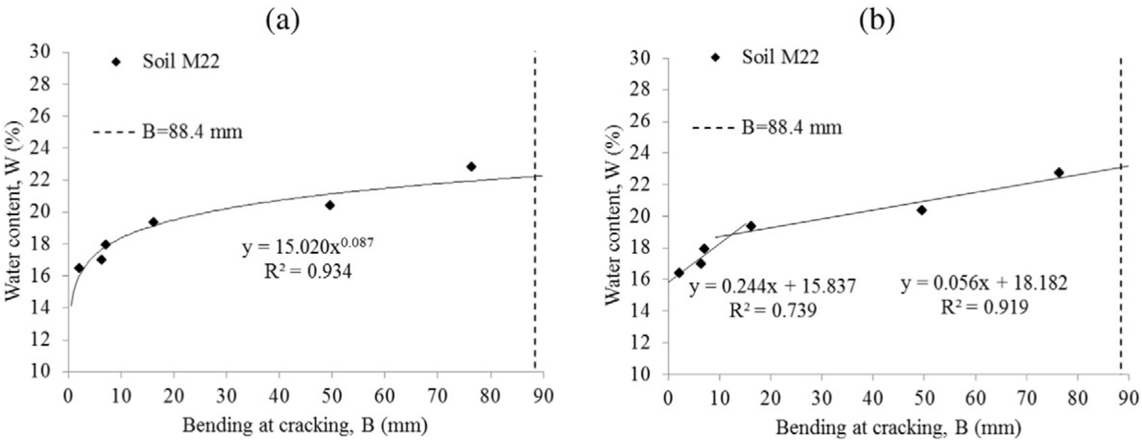

Fig. 6. Graphical representation of the B–W points for the soil M22 drawn as (a) a parabolic curve or (b) as two intersecting lines. Equations of the bending curve (a), stiff-plastic line and soft-plastic line (b) are included.

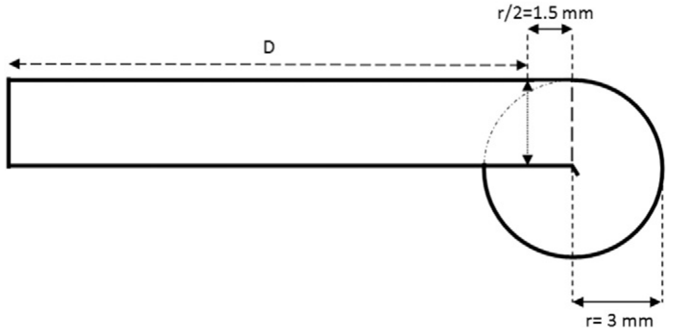

Fig. 7. Schematic representation of a fully bent 3 mm diameter × 52 mm length soil thread. The necessary dimensions to calculate the distance between the thread tips (D) are indicated (drawing is not to scale).

where j is j_{stiff} or j_{soft}, c is c_{stiff} or c_{soft} and B_{SS} is the bending at cracking, B, for the SSL moisture, which is obtained as:

$$B_{SS} = (c_{soft} - c_{stiff})/(j_{stiff} - j_{soft}) \tag{9}$$

Apart from the typical liquid, plastic and semisolid (or brittle) states defined by the LL and PL, the new parameters, SSL and BL, allow other consistency states in clays and cohesive soils within the plastic region to be delimited, such as stiff-plastic (between PL and SSL), soft-plastic (between SSL and BL) or very soft-sticky (between BL and LL) (Fig. 8a, b). However BL and SSL usually appear positioned above the LL in very low plasticity soils (Fig. 8a, d, f), and the consistency in this case between the LL and BL or SSL may be defined as liquid but not entirely deformable (the ability to be completely deformed is acquired when water contents are above BL). Similarly, it may occur that LL = BL or LL = SSL (Fig. 8a, c, e), so that in the former, the consistency changes directly from soft-plastic to liquid, and in the latter, from stiff-plastic to liquid which is not entirely deformable. Therefore, BL and SSL could

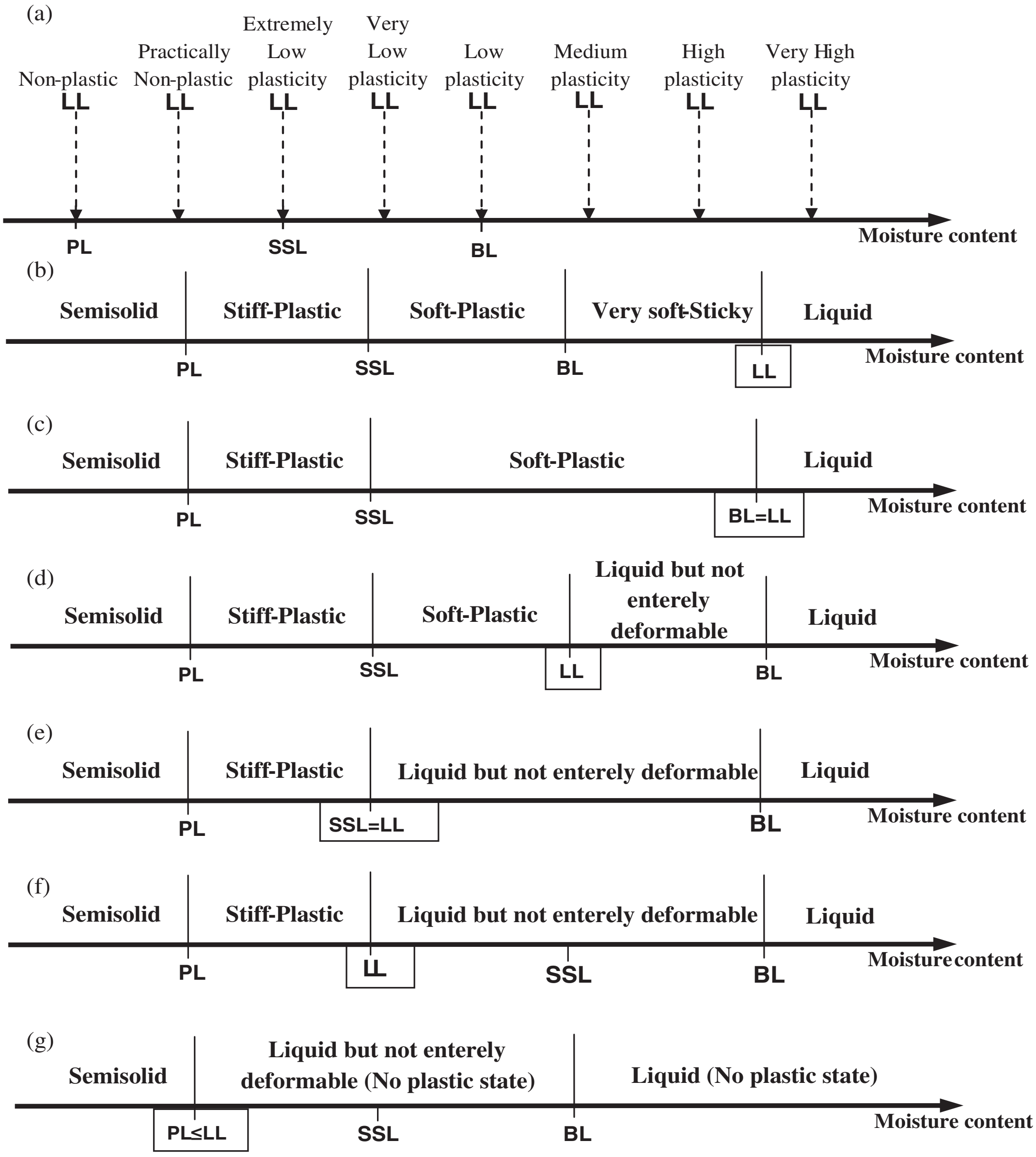

Fig. 8. (a) Schematic classification of soil plasticity depending on the LL value with regard to BL, SSL and PL. Consistency states identified in (b) medium, high and very high plasticity, (c) low plasticity, (d) very low plasticity, (e) extremely low plasticity, (f) practically non-plastic and (g) non-plastic soils. LL position is bordered to be more easily located in (b–g).

have great potential in geotechnical engineering, agriculture or above all in the ceramics industry, where the material consistency must be perfectly controlled in the LL–PL range to optimize production and obtain flawless products. With special regard to SSL, the moisture percentage marked by this parameter could be used as the optimum water content for molding ceramic clays, since below the SSL, the clay may crack more easily because of its stiffness, whereas above the SSL it could lose shape or stick to the work surfaces as it would be too soft. A schematic graph of the results and stiff-plastic and soft-plastic lines obtained in the soil M5 is represented (Fig. 9), since this clay has optimal plastic characteristics for ceramics (Marsigli and Dondi, 1997). SSL is represented as the optimum water content for molding this clay in a ceramic process because higher or lower water contents could affect negatively to the extrusion and molding process as indicated above.

Since neither the PL nor the SSL can be calculated from the bending curve (neither B = 0 values can be obtained from this nor can a specific transition point be readily recognized in the curve), a priori many points are required in order to successfully calculate the PL, BL and SSL from the straight lines, which entail increasing the test time. However, although the bending curve cannot be used for calculating the parameters it can be drawn properly with just a few points (in principle only 3 points would be required (this will be covered in Section 3.5)). Considering that the bending curve and the stiff-plastic–soft-plastic lines follow very similar paths, the bending curve equation obtained from the experimental data (Eq. (2)) has been used to obtain extra points to, firstly, correct any deviation, and, secondly, to carry out the test with just a few points. In order to unify the criteria the extra points calculated were those corresponding to B = 5, 7.5, 10, 15, 25, 35, 45, 55, 65 and 75 mm, which were well distributed along the entire x-axis. In particular instances one more point below B = 5 mm was added, but this is only recommendable when the stiff-plastic line has not been clearly defined with the other points. Even so, the value of this additional point should never be under the lowest of those experimentally obtained. The experimental points plus the extra ones were plotted, from which the stiff-plastic and soft-plastic lines were drawn and whose equations were obtained to determine PL, BL and SSL, as shown in Fig. 10 for the soil M22.

3.4. The plastic limit by the thread bending test and the new parameters

The results obtained for the 24 soil samples are shown in Table 3. As can be seen, the bending curve, stiff-plastic and soft-plastic line equations exhibited highly acceptable correlations, with high R^2 coefficients, so equations and data calculated from them were highly reliable.

Data shows that the PL results from the new thread bending test were quite similar to those obtained by a highly experienced operator using the standard test. In general the results obtained were slightly lower than those yielded from the thread rolling test. In 14 of the 24 samples tested, the results from the new bending test were somewhat lower than those obtained with the standard method whose results were higher in 9 soils and coincided in one (M11). Nevertheless, the differences perceived were quite narrow: the average of the difference $PL_{bending}$–$PL_{rolling}$ was only −0.4 percentage points with a standard deviation of 1.7, which in absolute value terms worked out at a difference of 1.3 percentage points with a standard deviation of 1.1. These differences always lied between a maximum and minimum value of 3.2 and −3.8 percentage points which corresponded to the samples M9 and M12 respectively.

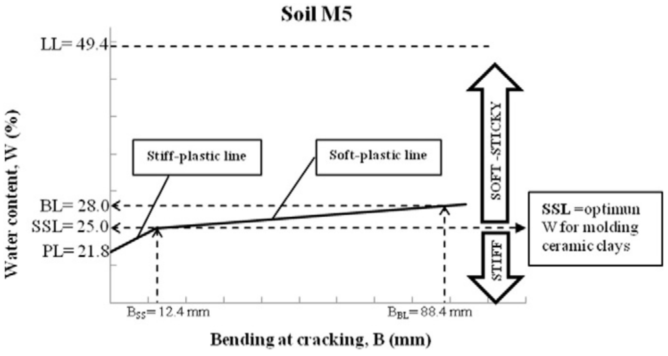

Fig. 9. Schematic graph of the results and stiff-plastic and soft-plastic lines obtained in the soil M5. SSL is represented as the optimum water content for molding this clay in a ceramic process.

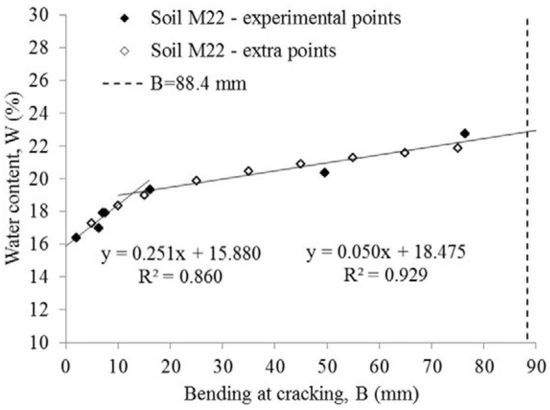

Fig. 10. Graphical representation of the experimental points together with the extra points for the soil M22 and the resulting stiff-plastic and soft-plastic lines and their equations.

This is more clearly demonstrated in Fig. 11, where the line formed between the PL results among the two tests is very close to the 1:1 line and where an excellent alignment of points can be observed ($R^2 = 0.972$). The PL-line and 1:1 line intersect at the point corresponding to PL = 23.9, so below this the general trend was for lower PL results to be obtained with the bending test than those from the rolling test and the opposite was true above the intersection point. Even so, the differences in the results yielded were very low.

To verify that there were no significant differences among the results, a Student's T test was applied after checking the data was normally distributed with a Shapiro–Wilk test using the software SPSS Statistics. As the soils were very heterogeneous, two different populations were differentiated: high plastic soils (soils M8, M9, M12 and M13), and medium and low plasticity soils (the rest of the soils). There was considered to be a confidence interval of 95%, i.e. with an alpha-level of 0.05. The Shapiro–Wilk test (Table 4) demonstrated that all the PL results were normally distributed, since the p-values were greater than 0.05 i.e. the null-hypothesis was accepted (the data had a normal distribution). Therefore a Student's T test could be applied.

As the p-values in the Student's T test were greater than the 0.05 alpha-level (Table 4), null-hypothesis was accepted, i.e. there were no significant differences between the PL results determined with both methods. Therefore, the thread bending test was very accurate, since its results were largely consistent with those obtained by a highly experienced operator. Nevertheless, it is highly likely that if the thread rolling test had been carried out by another operator, for example, one lacking in experience or skill, significant differences would have almost certainly been recorded. In fact, even for a highly experienced operator, the subjective judgment needed to appreciate the crumbling condition can change for soils with different characteristics. For the above reasons it can be reaffirmed that the new thread bending test is a more reliable method, with respect to the standard thread rolling test, for determining the plastic limit, since the bending test is accurate, free of subjective judgments and can be carried out with guarantees even by an inexperienced operator.

Table 3
Results obtained by the thread bending test.

Soil	Bending curve[a]	Stiff-plastic line[a]	Soft-plastic line[a]	$PL_{bending}$	$PL_{bending}$–$PL_{rolling}$	$PI_{bending}$	Casagrande class	BL	SSL	B_{SS}	LL–BL	LL–SSL	Exp. points	Extra points[b]	Total points
M1	$y = 18.375(x\hat{}\mathbf{0.113})$ $R^2 = 0.954$	$y = 0.476x + 19.101$ $R^2 = 0.873$	$y = 0.092x + 23.914$ $R^2 = 0.891$	19.1	**−0.2**	14.7	CL	32.0	25.1	12.5	1.8	8.7	7	10	17
M2	$y = 13.900(x\hat{}\mathbf{0.139})$ $R^2 = 0.949$	$y = 0.315x + 15.911$ $R^2 = 0.871$	$y = 0.083x + 19.540$ $R^2 = 0.972$	15.9	**−2.9**	11.0	CL	26.9	20.8	15.6	0.0	6.1	6	10	16
M3	$y = 18.136(x\hat{}\mathbf{0.097})$ $R^2 = 0.938$	$y = 0.273x + 19.651$ $R^2 = 0.939$	$y = 0.064x + 23.137$ $R^2 = 0.884$	19.7	**−1.3**	12.1	CL	28.8	24.2	16.7	3.0	7.6	4	10	14
M4	$y = 10.772(x\hat{}\mathbf{0.129})$ $R^2 = 0.988$	$y = 0.199x + 12.392$ $R^2 = 0.980$	$y = 0.052x + 15.108$ $R^2 = 0.961$	12.4	**−0.1**	3.9	ML	19.7	16.1	18.5	−3.4	0.2	5	10	15
M5	$y = 20.985(x\hat{}\mathbf{0.061})$ $R^2 = 0.962$	$y = 0.263x + 21.761$ $R^2 = 0.774$	$y = 0.039x + 24.530$ $R^2 = 0.950$	21.8	**0.8**	27.6	CL/CH	28.0	25.0	12.4	21.4	24.4	4	10	14
M6	$y = 14.125(x\hat{}\mathbf{0.093})$ $R^2 = 0.962$	$y = 0.478x + 13.626$ $R^2 = 0.912$	$y = 0.051x + 17.559$ $R^2 = 0.882$	13.6	**0.4**	14.4	CL	22.1	18.0	9.2	5.9	10.0	5	11[c]	16
M7	$y = 14.846(x\hat{}\mathbf{0.124})$ $R^2 = 0.972$	$y = 0.564x + 14.937$ $R^2 = 0.883$	$y = 0.076x + 20.046$ $R^2 = 0.965$	14.9	**0.3**	20.2	CL	26.8	20.8	10.5	8.3	14.3	5	10	15
M8	$y = 33.759(x\hat{}\mathbf{0.193})$ $R^2 = 0.996$	$y = 2.489x + 32.788$ $R^2 = 0.945$	$y = 0.380x + 51.449$ $R^2 = 0.965$	32.8	**2.7**	50.5	CH	85.0	54.8	8.8	−1.7	28.5	6	11[c]	17
M9	$y = 54.097(x\hat{}\mathbf{0.072})$ $R^2 = 0.991$	$y = 1.713x + 52.890$ $R^2 = 0.931$	$y = 0.169x + 62.556$ $R^2 = 0.937$	52.9	**3.2**	27.1	MH	77.5	63.6	6.3	2.5	16.4	5	10	15
M10	$y = 20.851(x\hat{}\mathbf{0.057})$ $R^2 = 0.965$	$y = 0.309x + 20.929$ $R^2 = 0.949$	$y = 0.040x + 23.903$ $R^2 = 0.965$	20.9	**0.9**	14.0	CL	27.4	24.3	11.1	7.5	10.6	5	10	15
M11	$y = 11.279(x\hat{}\mathbf{0.133})$ $R^2 = 0.989$	$y = 0.233x + 12.874$ $R^2 = 0.925$	$y = 0.054x + 16.162$ $R^2 = 0.982$	12.9	**0.0**	9.9	CL	20.9	17.2	18.4	1.9	5.6	3	10	13
M12	$y = 22.481(x\hat{}\mathbf{0.130})$ $R^2 = 0.997$	$y = 0.622x + 24.344$ $R^2 = 0.982$	$y = 0.122x + 30.864$ $R^2 = 0.972$	24.3	**−3.8**	38.2	CH	41.6	32.5	13.0	20.9	30.0	5	10	15
M13	$y = 33.906(x\hat{}\mathbf{0.072})$ $R^2 = 0.985$	$y = 0.360x + 36.218$ $R^2 = 0.971$	$y = 0.080x + 40.621$ $R^2 = 0.966$	36.2	**−0.9**	178.2	CH	47.7	41.9	15.7	166.7	172.5	4	10	14
M14	$y = 14.990(x\hat{}\mathbf{0.129})$ $R^2 = 0.972$	$y = 0.247x + 17.490$ $R^2 = 0.942$	$y = 0.071x + 21.216$ $R^2 = 0.939$	17.5	**−2.5**	12.0	CL	27.5	22.7	21.2	2.0	6.8	7	10	17
M15	$y = 13.337(x\hat{}\mathbf{0.101})$ $R^2 = 0.979$	$y = 0.170x + 14.976$ $R^2 = 0.984$	$y = 0.044x + 17.470$ $R^2 = 0.984$	15.0	**−1.2**	6.9	CL–ML	21.4	18.3	19.8	0.5	3.6	3	10	13
M16	$y = 13.952(x\hat{}\mathbf{0.101})$ $R^2 = 0.982$	$y = 0.200x + 15.442$ $R^2 = 0.969$	$y = 0.045x + 18.326$ $R^2 = 0.980$	15.4	**−0.6**	10.8	CL	22.3	19.2	18.6	3.9	7.0	4	10	14
M17	$y = 14.727(x\hat{}\mathbf{0.099})$ $R^2 = 0.984$	$y = 0.147x + 16.799$ $R^2 = 0.930$	$y = 0.047x + 19.237$ $R^2 = 0.980$	16.8	**−0.3**	20.1	CL	23.4	20.4	24.4	13.5	16.5	3	10	13
M18	$y = 15.448(x\hat{}\mathbf{0.079})$ $R^2 = 0.989$	$y = 0.357x + 15.619$ $R^2 = 0.968$	$y = 0.050x + 18.357$ $R^2 = 0.954$	15.6	**0.7**	14.7	CL	22.8	18.8	8.9	7.5	11.5	5	10	15
M19	$y = 9.932(x\hat{}\mathbf{0.145})$ $R^2 = 0.851$	$y = 0.232x + 11.568$ $R^2 = 0.872$	$y = 0.070x + 13.853$ $R^2 = 0.955$	11.6	**−2.1**	10.4	CL	20.0	14.8	14.1	2.0	7.2	6	10	16
M20	$y = 17.617(x\hat{}\mathbf{0.085})$ $R^2 = 0.868$	$y = 0.175x + 19.171$ $R^2 = 0.799$	$y = 0.037x + 22.702$ $R^2 = 0.703$	19.2	**1.3**	13.9	CL	26.0	23.6	25.6	7.1	9.5	6	10	16
M21	$y = 9.901(x\hat{}\mathbf{0.140})$ $R^2 = 0.869$	$y = 0.202x + 11.525$ $R^2 = 0.979$	$y = 0.056x + 14.177$ $R^2 = 0.953$	11.5	**−2.2**	2.8	ML	19.1	15.2	18.2	−4.8	−0.9	5	10	15
M22	$y = 15.020(x\hat{}\mathbf{0.087})$ $R^2 = 0.934$	$y = 0.251x + 15.880$ $R^2 = 0.860$	$y = 0.050x + 18.475$ $R^2 = 0.930$	15.9	**−0.1**	15.7	CL	22.9	19.1	12.9	8.7	12.5	6	10	16
M23	$y = 16.111(x\hat{}\mathbf{0.095})$ $R^2 = 0.934$	$y = 0.251x + 17.437$ $R^2 = 0.974$	$y = 0.067x + 19.889$ $R^2 = 0.921$	17.4	**0.4**	31.3	CL	25.8	20.8	13.3	22.9	27.9	6	10	16
M24	$y = 13.343(x\hat{}\mathbf{0.120})$ $R^2 = 0.997$	$y = 0.340x + 14.310$ $R^2 = 0.979$	$y = 0.062x + 18.048$ $R^2 = 0.952$	14.3	**−1.3**	11.9	CL	23.5	18.9	13.4	2.7	7.3	4	10	14
av. *m*[d]	0.108			av.	**−0.4**				av.	15.0					
sd *m*[d]	0.032			sd	**1.7**				sd	4.9					
av. *m*[e]	0.108			max	**3.2**				max	25.6					
sd *m*[e]	0.033			min	**−3.8**				min	6.3					

[a] y = W and x = B in the equations.

[b] Number of extra points included in the analysis. Extra points are those calculated for B = 5, 7.5, 10, 15, 25, 35, 45, 55, 65 and 75 mm.

[c] Other than indicated on [b], an additional extra point was added: B = 2 mm in M6 and B = 3 mm in M8.

[d] Average and standard deviation of the bending slopes, *m*, that appear in bold in each bending curve equation

[e] Average and standard deviation of the bending slopes, *m*, that appear in bold in each bending curve equation but 3-point soils (M11, M15 and M17) are not included.

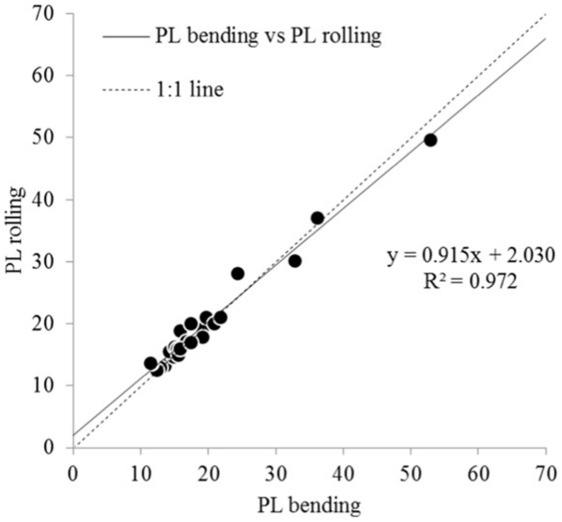

Fig. 11. Plastic limit results from the new thread bending test against those from the traditional thread rolling test.

The Plasticity index, PI, is directly related to the PL value (PI = LL–PL), so the same variations observed in the PL have been perceived in the PI (Table 3). As the PL differences between the methods are quite small, the PI results have not changed significantly and thus, no change in the Casagrande classification has been registered.

Concerning the new parameters (which are the bend-breaking limit, BL, and the stiff-soft limit, SSL, in Table 3) a wide variety of results can be seen, most of which show values around 20 to 30, although in more plastic soils, M8, M9, M12 and M13, greater BL and SSL values were exhibited. The LL position regarding BL and SSL (LL–BL and LL–SSL columns) revealed LL to be greater than BL in most cases. Nevertheless BL was higher than LL in soils M4, M8 and M21, which indicated that between the LL and the BL there was a consistency state that despite being liquid, was not entirely deformable. For the soil M21, SSL was higher than LL, because this was essentially a nonplastic soil. The M8 soil had unusual properties, since although LL and PI values were high, there was poor resistance to bending. A DRX analysis with a Philips ® X'Pert MPD X-ray diffractometer revealed that in the M8 soil there was a great deal of calcite combined with smectite which was the main clay component. The smectite could explain why there was high LL and PI, since smectite minerals are related with very high Atterberg limits results (White, 1949), whereas the calcite could explain the low bending capacity because this acts as a cement that affects the soil properties and reduces the plasticity (Datta et al., 1982). In the M2 soil, LL = BL, so the consistency changed directly from soft-plastic to liquid, and there was no detection of any consistency that was very soft or sticky within the plastic state. Furthermore, the B_{SS} results indicate that the stiff-soft limit is normally located at an average of B = 15 mm, but this value changes at intervals between 6.3 (M9) and 25.6 (M20). All these new parameters, therefore, show other features that may be of interest and that LL and PL cannot obtain by themselves.

Table 4
Test of normality of Shapiro–Wilk for PL results of high and low-medium plasticity soils according to bending and rolling tests. In bold, test of Student's T for the results of PL obtained by the thread bending test against the thread rolling test; high and low-medium plasticity soils are differentiated.

Variable	Statistic	df	p-Value
Shapiro–Wilk test for PL bending high plasticity	0.947	4	0.700
Shapiro–Wilk test for PL rolling high plasticity	0.897	4	0.414
Shapiro–Wilk test for PL bending low-medium plasticity	0.968	20	0.708
Shapiro–Wilk test for PL rolling low-medium plasticity	0.943	20	0.276
Student's T test (bilateral) for PL of high plasticity soils	**0.183**	**3**	**0.867**
Student's T test (bilateral) for PL of low-medium plasticity soils	**−1.833**	**19**	**0.083**

3.5. Feasibility of the method using only 3 points and the importance of the bending slope, *m*

The soils M11, M15 and M17 were tested with only 3 points. In order to verify if the results obtained from these three samples were correct and if a 3-point test would be reliable, a statistical study of samples M2, M8, M19, M20, M22, M23, M1 and M14 (the samples with the greatest number of experimental points) was conducted. Those soils with 6 (M2, M8, M19, M20, M22 and M23) and 7 points (M1 and M14) were the ones used, so every possible combination of 3 points was studied (20 different combinations were obtained in each 6-point soil and 35 in each 7-point soil, i.e. there were 190 combinations in total). Bending curves were determined from each 3-point combination, so that the same extra points as those included in Table 3 were calculated from the bending curve equation. The 3 experimental points together with the extra points were used to draw the stiff-plastic lines and soft-plastic lines and thus, PL, BL and SSL were obtained and compared to the original 6 or 7 experimental point results (the reference). In accordance with the maximum acceptable difference for two PL results as stated in UNE 103–104 -93, those results obtained from the use of just 3 experimental points that differed by more than 2 percentage points with respect to the reference were considered to be "inaccurate". Since a large amount of data was extracted, Table 5 shows a summary of the results. The overall percentage of correct (accurate) results was very high (91.1% for PL, 83.7% for BL and 98.4% for SSL). Moreover, there was a strong relationship between the bending slope, *m*, and the number of correct results. The average of the bending slope, *m*, in the soils tested (without the 3-point soils M11, M15 and M17) was 0.108 with a standard deviation of 0.033 (*m* values are shown in bold in the bending equations in Table 3). Then, there was an excellent success percentage (PL = 99.3 %, BL = 87.0% and SSL = 100%) with the data calculated from a bending curve equation in which *m* had a value between 0.058 and 0.158 (1.5 standard deviation range). These are also shown in bold in Table 5. In contrast, for *m* values outside the 1.5 sd range (i.e. $m > 0.158$ or $m < 0.058$) the percentage of inaccurate data rose, so the success percentage dropped to only 63.6% for PL, 72.7% for BL and 93.2% for SSL. Therefore, a very quick 3-point method was feasible so if the experimental bending slope is between 0.058 and 0.158 the results can be considered "correct" and if *m* is outside this range, then obtaining more experimental points is recommended. Hence, the M11, M15 and M17 results were correct since their bending slopes lay between said range.

3.6. A one-point thread bending method

The liquid limit of soil was calculated using international standards by means of an equation dependent on the most probable slope of the flow line from a statistical point of view (e.g. this slope was 0.117 for UNE 103-103-94, and 0.121 for ASTM D 4318–05).

By using the same principle, with only one experimental point the stiff-plastic and soft-plastic lines could be calculated and with them the PL, BL and SSL. The bending slope, *m*, of the 24 tested soils was 0.108 with a standard deviation of 0.032 (Table 3), from which the following equation was obtained:

$$W_{extra} = W_{exp} \cdot \left(B_{exp}/B_{extra}\right)^{-0.108} \tag{10}$$

where W_{exp} and B_{exp} show the water content and the point bending obtained experimentally, respectively. B_{extra} is the bending of the extra point added in the analysis and W_{extra} is the water content of that extra point.

Table 5
Summary of the results of 190 combinations of 3 points from those soils tested with 6 and 7 points and relationships regarding the bending slope, *m*.

	PL	BL	SSL
Total number of 3-point combinations	190	190	190
Total number of correct results and (% success)	173 (91.1)	159 (83.7)	187 (98.4)
No. combinations within the range 1.5 sd ($0.058 < m < 0.158$)	146	146	146
No. of correct results and (% success) within the range 1.5 sd	**145 (99.3)**	**127 (87.0)**	**146 (100)**
No. combinations outside the range 1.5 sd	44	44	44
No. of correct results and (% success) outside the range 1.5sd	28 (63.6)	32 (72.7)	41 (93.2)

Every point was substituted into Eq (10). The extra points (B_{exp}) were those indicated in Table 3. Each experimental point together with its extra points were plotted and the stiff-plastic and soft-plastic lines were drawn. PL, BL and SSL were calculated and compared with the results for all the points shown in Table 3. Those results that differed by more than 2 percentage points with respect to the reference were considered to be "inaccurate". As can be seen in Table 6 said results were highly satisfactory. From a total of 119 results, 108 for PL and 107 for SSL were highly accurate since they differed by less than 2 percentage points with respect to the reference, i.e. for these two parameters 90.8% and 89.9% of results were accurate. There was a greater deviation with BL which had a success percentage of 68.9%. Thus, in general all soils showed excellent results with the one-point test. This was corroborated in Fig. 12, where the average results of the one-point test was plotted against the reference results with all the original points. Only the soils M8 and M9 showed deviation with the BL results (Fig. 12b), whereas for all other data there was excellent concurrence in the graphs, with high correlations (R^2 of 0.976, 0.907 and 0.986 for PL, BL and SSL respectively) and regression lines that fitted very closely to the 1:1 line, so this one-point test could be considered to be as reliable a method as the multi-point test. In order to improve accuracy even more, two experimental points with different B values are recommended in this one-point test and if the differences are not greater than 2 percentage points, the test can be considered satisfactory with the final result being the average of the two experimental points. If these differ by more than two percentage points, more experimental data should be obtained. As a final point, it can be said that this version of the thread bending test is not only more accurate but also quicker than the thread rolling test in PL determination.

4. Conclusions

The thread rolling test is inadequate for determining the PL, as it is highly dependent on the skill and judgment of the operator who is carrying out the test. However its simplicity, low cost and speed give it an advantage over the unsuccessful alternatives proposed to date.

For this reason, the method presented in this paper (the thread bending test), based on the measurement of bending deformations, has been presented as a real alternative with potential to replace the outdated thread rolling test and to become normalized, because apart from being simple, rapid and inexpensive, it is also accurate and free of subjective judgments.

Additionally, the new parameters defined by the thread bending test allow other soil consistency states apart from the typical plastic and liquid states to be identified, which will certainly be useful in sectors such as the ceramics industry, agriculture and geotechnical engineering.

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Table 6
Results of the one-point bending method for each point experimentally obtained. Data are written as PL; BL; SSL. In bold those results that differ in more than 2 points respect to the reference.

Soil	Reference	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7
M1	19.1; 32.0; 25.1	18.8; 31.5; 25.6	19.6; 31.1; 25.4	20.1; 30.9; 25.3	19.3; **29.3**; 23.9	19.7; **29.8**; 24.4	20.9; 31.6; 26.0	**21.6**; 32.8; 26.8
M2	15.9; 26.9; 20.8	16.6; **24.7**; 20.4	16.2; **23.8**; 29.7	16.7; **24.7**; 20.4	17.7; 26.2; 21.6	17.2; 25.4; 21.0	17.8; 26.4; 21.8	NA
M3	19.7; 28.8; 24.2	19.1; 30.3; 24.7	19.1; 28.8; 23.6	19.0; 28.8; 23.5	19.9; 30.2; 24.8	NA	NA	NA
M4	12.4; 19.7; 16.1	12.8; 18.7; 16.0	12.9; 19.0; 16.0	13.2; 19.4; 16.6	13.0; 19.0; 16.2	13.1; 19.2; 16.4	NA	NA
M5	21.8; 28.0; 25.0	21.1; **32.4**; 26.5	21.6; **32.7**; 26.8	19.9; **30.2**; 23.7	**19.5**; 28.9; 23.8	NA	NA	NA
M6	13.6; 22.1; 18.0	14.0; **24.2**; 19.6	13.9; 22.1; 17.9	13.7; 22.7; 17.7	14.8; 23.7; 19.2	13.8; 22.0; 17.9	NA	NA
M7	14.9; 26.8; 20.8	14.9; **24.5**; 19.9	16.2; 25.0; 20.4	**17.8**; 27.0; 20.2	16.9; 25.7; 21.0	**17.2**; 26.1; 21.3	NA	NA
M8	32.8; 85.0; 54.8	32.7; **55.8; 43.7**	34.8; **58.2; 45.6**	**36.2**; **60.2**; **47.2**	**40.7; 64.9; 51.1**	**45.5; 71.3; 57.3**	**44.9; 70.2;** 56.5	NA
M9	52.9; 77.5; 63.6	52.4; **90.8; 71.1**	54.0; **86.0; 66.9**	**55.2; 89.0; 70.0**	54.1; **83.7; 66.3**	53.9; **84.1; 65.7**	NA	NA
M10	20.9; 27.4; 24.3	21.0; **35.2; 28.6**	20.6; **32.3**; 26.3	20.1; **30.7**; 24.7	20.2; **30.6**; 24.8	19.5; **29.6**; 24.2	NA	NA
M11	12.9; 20.9; 17.2	12.9; 19.1; 16.3	13.6; 19.9; 17.0	13.9; 20.3; 17.4	NA	NA	NA	NA
M12	24.3; 41.6; 32.5	24.5; **38.8**; 31.6	25.6; **38.7**; 31.7	25.7; **38.9**; 31.9	26.3; 39.9; 32.6	**27.3**; 41.4; 34.0	NA	NA
M13	36.2; 47.7; 41.9	34.9; **53.6**; 43.8	35.1; **51.9;** 42.8	35.2; **52.3**; 42.6	**32.8;** 48.6; 40.1	NA	NA	NA
M14	17.5; 27.5; 22.7	17.9; 26.4; 22.5	17.3; **25.3**; 21.6	17.9; 26.3; 22.4	17.5; 25.7; 21.9	18.0; 26.3; 22.5	18.6; 27.3; 23.3	18.6; 27.3; 23.2
M15	15.0; 21.4; 18.3	14.6; 21.6; 17.8	14.9; 22.1; 18.2	14.5; 21.5; 17.8	NA	NA	NA	NA
M16	15.4; 22.3; 19.2	15.4; 22.3; 19.2	15.3; 22.5; 19.2	15.5; 22.7; 19.4	15.7; 23.1; 19.3	15.1; 22.1; 18.8	NA	NA
M17	16.8; 23.4; 20.4	16.4; 24.1; 20.6	15.8; 23.4; 19.5	16.1; 23.6; 20.1	NA	NA	NA	NA
M18	15.6; 22.8; 18.8	16.3; **25.4; 21.5**	16.6; 24.4; 20.8	15.8; 23.0; 19.7	15.5; 22.7; 19.4	15.6; 22.8; 19.5	NA	NA
M19	11.6; 20.0; 14.8	12.8; 18.9; 15.6	12.2; 18.1; 15.0	12.0; **17.8**; 14.7	12.5; 18.5; 15.3	13.2; 19.6; 16.2	13.6; 20.0; 16.6	NA
M20	19.2; 26.0; 23.6	19.1; **29.8**; 24.5	18.1; 26.8; 22.1	18.0; 26.6; 21.8	19.4; **28.7**; 23.7	18.0; 26.6; 22.0	18.6; 27.5; 22.8	NA
M21	11.5; 19.1; 15.2	12.5; 18.4; 15.4	12.4; 18.2; 15.3	12.1; 17.8; 15.2	12.3; 18.0; 15.4	13.0; 19.0; 16.2	NA	NA
M22	15.9; 22.9; 19.1	15.8; **25.3**; 20.6	15.4; 23.2; 19.0	16.0; 24.2; 19.8	15.7; 24.0; 19.4	14.7; 22.3; 18.3	15.7; 23.6; 19.5	NA
M23	17.4; 25.8; 20.8	17.3; 27.3; 22.3	17.2; 26.1; 21.3	17.1; 25.8; 21.3	16.4; 24.9; 20.4	16.5; 25.1; 20.6	17.6; 26.6; 21.9	NA
M24	14.3; 23.5; 18.9	14.4; 22.5; 18.4	15.1; 22.9; 18.8	15.1; 22.9; 18.8	15.4; 23.4; 19.2	NA	NA	NA

NOTE: The points are in ascending order of bending, i.e., the Point 1 is the one whose experimental B is the lowest whereas the point 7 (or the applicable in those samples with less than 7 points) is the one with the highest B.
NA: Not applicable.

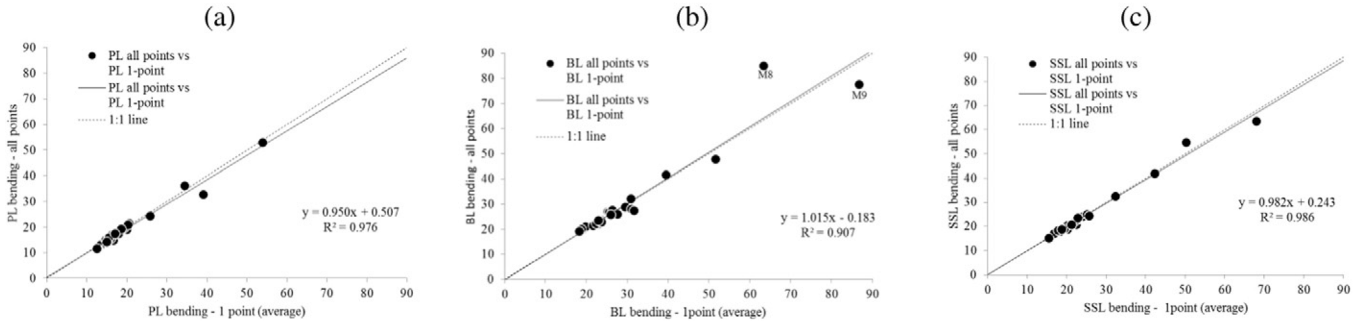

Fig. 12. Results obtained by the bending test with all the experimental points against the average of those obtained with only 1 point for (a) the PL, (b) the BL and (c) the SSL.

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