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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