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Research paper

An apparatus for the determination of the workability and plastic limit of clays

G.E. Barnes *

Consultant in Geotechnical Engineering, 32 Greenfield Avenue, Urmston, Manchester, England M41 0XN, United Kingdom

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ABSTRACT

An apparatus is described that replicates Atterberg's procedure of rolling a thread of clay for the determination of the plastic limit of soils with minimal operator interference or judgement of the crumbling condition required. From nominal stresses applied during rolling and changes in diameter measured for each rolling traverse the toughness of the clay is determined from the stress–strain curves, as work/unit volume for a specified amount of deformation. Threads are tested at water contents ranging from near the sticky limit through the workable plastic region to the brittle state. An abrupt ductile–brittle or plastic–brittle transition is found allowing the plastic limit to be defined as the transition water content. A less abrupt but distinct stiffness transition is frequently obtained that separates the workable plastic region into a soft-plastic and a stiff-plastic region. Good relationships between toughness and water content are achieved from which the maximum toughness, T_{max}, at the plastic limit is derived together with other new and useful properties such as the water content at the stiffness transition, w_S and at zero toughness, the toughness limit, w_T. Also derived are the gradients of the relationships, the toughness coefficients, T_C, the range of water contents over which the clay is plastic and tough, the toughness index, I_T and the water content in relation to the toughness index, the workability index, I_w. Each clay is found to have a closely correlated toughness–water content relationship depending mainly on the clay content and clay mineralogy demonstrating that control of the plasticity of the clay and its associated water contents are achievable.

1. Introduction

The test procedures for the plastic limit and liquid limit as first devised by Atterberg (1911, 1974) were fairly simple attempts to investigate the transitions at each end of the plasticity range of mainly clay soils. Between these water contents the soil is deemed to be plastic. However, Atterberg noted that the degree of plasticity does not lend itself to measurement and although a range of devices has since been produced none of these provide a satisfactory quantitative measure of a clay's ability to change shape without rupturing, as pointed out by several authors including Dinsdale (1986), Händle (2009), Reeves et al. (2006), Ryan and Radford (1987), and Worrall (1982).

A widely used test that purports to determine a measure of plasticity is the Pfefferkorn method although this test is criticised (Modesto and Bernardin, 2008) because the value obtained is a water content, not a measurement of plastic deformation or resistance to a force and the test is less reproducible with stiffer clays.

The Brabender plastograph is a fairly crude device acting as a torque rheometer (West and Lawrence, 1959) that can be used to obtain a torque–water content relationship with the clay's plasticity interpreted as either a maximum torque value or the range of water contents over which the clay is plastic (Andrade et al., 2011). To investigate the flow characteristics of ceramic bodies a commonly used device is the capillary rheometer, particularly as it can be adapted to investigate operational conditions (Andrade et al., 2011). However, the flow processes that occur during extrusion are very complex, involving many conflicting effects (Gleissle and Graczyk, 2009).

There are several penetrometer instruments that can be pushed into a clay to give a reading of force or pressure (Göhlert and Uebel, 2009) but these relate to the static shear strength of the clay not its plasticity or deformation characteristics and the results can be affected by the depth and rate of penetration.

Dinsdale (1986) indicated that a form of compression test would be best suited to evaluate plasticity "…any method of measurement that will provide the required stress–strain curves will give the necessary control guidance". Ribeiro et al. (2005) describe compression stress tests on cylindrical samples of clay deformed up to 70% axial strain. However, these large deformations result in a significant change in specimen shape with increasing shear stresses at the ends of the cylinders, although greased platens could be used (Moore, 1963; Rowe and Barden, 1964) to reduce this effect.

This paper introduces an apparatus that was initially devised to replicate as far as possible Atterberg's manual rolling thread procedure for the plastic limit but serendipitously provides a method for determining a measure of plasticity. An amount of work per unit volume can be determined from a stress–strain curve as the toughness of the clay when the clay thread is undergoing deformation in the fully plastic and ductile

* Tel.: +44 161 747 9560.
E-mail address: grahamebarnes@virginmedia.com.

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state. The transition between the ductile and the brittle states is clearly identified in the test giving an accurate determination of the plastic limit.

The apparatus and test method provide stress–strain curves with minimal interference from the operator and the subjective judgement of a crumbling condition at the plastic limit is eliminated. Because the specimen tested benefits from minimal restriction in its freedom of movement subtle changes in soil behaviour can be detected, particularly with respect to its water content.

2. Plasticity and workability

Atterberg (1911, 1974) gave his definition of plasticity as the ability of a soil to be rolled out into threads and described a manual rolling-out test which identified the plastic limit as the water content when the threads crumbled. He found that some clays could be rolled out to much thinner threads than others, but rolling out thin threads of clay is more related to the property of ductility, rather than plasticity, as this term is usually associated with the drawing out of metal wires. This ability would also be related to the property of cohesion or tenacity, as thin clay threads must be able to resist breaking. In the absence of anything better at the time (1911), Atterberg suggested that the plasticity index, the difference between the liquid and plastic limits, could be used to denote the degree of plasticity.

In geotechnical engineering, plasticity is defined (BS EN ISO 14688-1:2002) as "the property of a cohesive soil to change its mechanical behaviour with change of moisture content" and, invoking the use of the Atterberg limits, as "soils that permit their consistency limits to be determined may be identified as exhibiting plastic properties".

In the ceramics industry plasticity is usually viewed as the property or ability of a clay to be deformed and change shape and to retain the shape permanently without fracture (Moore, 1963; Onoda, 1996; Reed, 1995). Many clays display this ability but they differ in the effort (force, work, energy) required to change the shape. This effort can be represented by the property of toughness, as an amount of work per unit volume required to produce a certain amount of deformation.

The plasticity of a clay is related to its water content. The range of water contents over which a clay can be moulded or worked together with the ease or difficulty of working, measured by its toughness, can be used to represent workability.

3. The apparatus

The apparatus comprises a rolling device that replicates the manual rolling procedure on a plastic soil thread, starting from a diameter of about 8 mm down to the diameter of 3 mm or so, but without interference from the operator. The apparatus was first described in Barnes (2009) and a detailed description of the apparatus, its operation and calculations for the various parameters is given in Barnes (2010).

An updated version of the apparatus is presented in Fig. 1, with a side view in Fig. 2 and a cross section in Fig. 3. The soil thread is placed between a top glass plate and a stainless steel base plate, both 50 mm wide overall and is rolled forward and back (left and right) under the loading bar by moving the support plate forward and back, for one traverse.

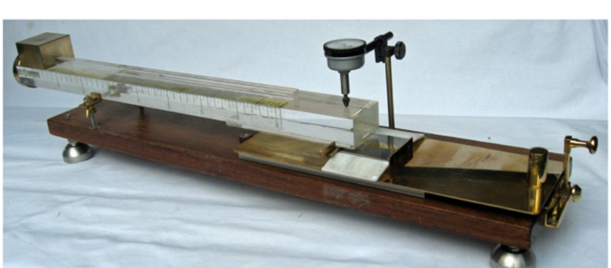

Fig. 1. View of apparatus.

The top and bottom plates are configured with a central 10 mm wide flat strip and the outer edges of the plates gently inclined outwards, at 1 in 40, or 0.5 mm in 20 mm to encourage longitudinal extrusion of the thread. As soft moist soils can stick to the plate surfaces, the glass in particular, a very thin smear of petroleum jelly is applied to the outer faces of both plates to prevent adhesion on these faces and to encourage extrusion.

The loading bar above the top glass plate is kept near horizontal so that a fairly uniform stress is applied to the thread on each traverse. The loading bar is made of transparent polycarbonate so that the behaviour of the thread can be viewed at all times.

In the ductile state, with fairly rapid rolling of the thread, the loading applied can be visualized as quasi 'all-round' diametral stresses that cause reduction in diameter and extrusion and elongation of the thread along its long axis. In reality the soil thread must undergo a complex process of compression and tension, possibly with some torsion and bending. In the brittle state, from consideration of the analysis of the split cylinder test (ASTM D3967-08) cycles of compression and tension across the thread diameter can be envisaged that ultimately result in failure by fracturing.

4. Preparation of the soil thread

Soil prepared initially at a water content for the liquid limit test is adopted to provide adequate hydration of the clay minerals. It is necessary to avoid the soil sticking to the plates of the apparatus so following the liquid limit test the soil is gently dried to below the sticky limit by warm air blowing and moulding in the hands to commence the tests. The tests then proceed by drying from a high water content. This is considered preferable to wetting up since the latter has been found, with the apparatus, to give a less effective water content due to incomplete mixing.

A thread of clay about 8 mm diameter and 60 mm long is prepared by static compaction in a specially made tubular device, a thread maker, see Fig. 4. A soil thread rolled by hand to less than 8 mm diameter is inserted into the sampling tube. The stopper and rammer are inserted and pressed together to statically compact the soil. Air is expelled via the 0.5 mm diameter hole in the side of the sampling tube. This provides a sufficiently intact and near-saturated specimen with any obvious defects or large air voids removed and with a circular shape suitable for rolling. The clay thread is then pushed by the rammer to the mark A leaving 60 mm inside the tube. The surplus is trimmed off and the thread is then extruded onto the bottom plate of the apparatus. It overlaps the width of the plates to ensure that a complete length of thread is always present between the plates.

The apparatus appears to be more sensitive to the presence of high coarse grain contents (sand or silt) than with the manual rolling method. It is imperative, therefore, that all soils to be tested are sieved to remove particles greater than 425 μm, and for natural soils this should be done preferably by wet sieving. This particle size complies with the requirements of BS 1377:1990, ISO/TS 17892-12:2004, and ASTM D4318-10 for the plastic limit test.

5. Test procedure

The stress on the thread is determined as a nominal stress from the formula derived from the analysis of the split cylinder or the Brazilian test (ASTM D3967-08)

$$\sigma = \frac{kF}{Ld} \tag{1}$$

where L is the length of the thread between the plates, in this case 50 mm, d is the diameter, and F is the force applied by the loading