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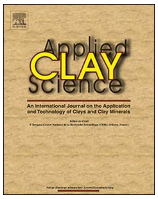

Note

Workability of clay mixtures

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ABSTRACT

Raw clays undergo mixing for the manufacture of structural clay products and ball clays and kaolins are carefully selected, processed, stored and blended in various proportions to produce consistent formulations for the wide range of fine ceramic products. The effects of blending different clays with a range of proportions have been investigated on the Atterberg plasticity limits and on the toughness-water content relationships. It is demonstrated that blending of raw and processed clays with different mineralogy and plasticity properties can produce liquid and plastic limits and toughness-water content relationships that do not follow a linear interpolation between the individual properties of the clays in relation to their proportions. Mixing of high plasticity clay with a lower plasticity clay produced a wider range of water contents over which the mixtures remained plastic, particularly with lower water contents which would be desirable when considering shrinkage properties. However, this resulted in increased toughness and harder workability, a less desirable factor.

1. Introduction

As a property of plastic clay workability is of fundamental importance in the manufacture of heavy clay products and fine ceramic products. Plasticity is usually viewed as the property or ability of clay in its fully plastic ductile state to be deformed and change shape and to retain the shape permanently without fracture whereas workability can be regarded as the ease or difficulty with which the material is worked or deformed. It is often suggested that plasticity can be defined by a maximum applied force or strength together with the amount of elongation the material can sustain. By their nature clays display plasticity but they differ in the effort required to produce deformation. This effort can be represented by the amount of work per unit volume required to produce a certain amount of deformation in the fully plastic state, referred to as the property of toughness. This can be quantified from the area beneath a stress-strain curve obtained from a test involving stress application of a material specimen. For clays toughness is mainly dependent on the clay content, mineralogy and water content.

Regarding the clay's water content the plasticity investigations of Atterberg (1911) identified a wide range of states with particular water contents at the (sometimes arbitrary) boundaries between these states. In soil mechanics the most commonly used terms are the liquid limit, identified as the water content representing the lower limit of viscous flow and the upper limit of plasticity, and the plastic limit, being the water content at the lower end of the plasticity range. Below the plastic limit the clay would behave in a brittle, friable manner. An intermediate water content, at the sticky (or adhesion) limit, was also identified as the lower limit of adhesion of the soil to metallic surfaces but this is rarely used. Many years ago Kinnison (1915) observed that the most workable range of water contents for the plastic state of clay was between the adhesion limit and the plastic limit, referred to as the 'normal consistency'.

It is suggested that a useful representation of overall workability of a clay can be viewed as a coupling of the two factors, toughness of a 'normal consistency' clay and the range of water contents over which the clay can be effectively worked.

A range of devices has been produced over the years with the aim of providing a measure of plasticity, mainly associated with ceramic processes. They include torque devices (Norton, 1938; Parmelee and Rudd, 1929; West and Lawrence, 1959; Brabender plastograph), compression devices (Fitzjohn and Worrall, 1980; Moore, 1963; Ribeiro et al., 2005), impact devices (Andrade et al., 2011; Modesto and Bernardini, 2008), extrusion devices (Händle, 2009; Gleissle and Graczyk, 2009) and penetrometer devices (Göhlert and Uebel, 2009). These devices, either directly or indirectly, produce a measure of the shear resistance of the clay but they give limited information on the strain response of the clay when in a fully plastic state and they are not particularly sensitive to changes in the properties measured. Several authors, including Worrall (1982), Dinsdale (1986), Ryan and Radford (1987), Reeves et al. (2006) and Händle (2009), have pointed out the significant difficulties of testing and measuring a clay's plasticity let alone providing a satisfactory quantitative value for this property.

An apparatus and test devised by the author, fully described elsewhere (Barnes, 2009, 2013a, 2013b) and summarised below, produces

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rolling and extrusion of a thread (small diameter cylinder) of clay in its fully plastic state. From a stress-strain curve produced during this process a measure of the work/unit volume, the toughness, is determined over a specified deformation within the fully plastic state. The test is repeated over the range of water contents from just below the adhesion limit down to the plastic limit.

Mixing, homogenisation and processing of clays for manufacturing structural clay products is of fundamental importance to ensure uniformity of the finished products. For fine ceramic clay production ball clays and kaolins are carefully selected, processed, stored and blended in various proportions to produce consistent formulations for the wide range of manufactured products. An investigation of the effects of blending different ceramic clays with a range of proportions on the toughness-water content relationships is described in this paper.

2. Experimental methods and materials

2.1. The apparatus

The author's apparatus and test method, described in detail elsewhere (Barnes, 2009, 2013a, 2013b), was designed to replicate the rolling process on a thread of clay as described in Atterberg's original procedure and in the standard plastic limit test (ASTM D4318-17, 2017; BS 1377-2, 1990; ISO/TS 17892-12, 2004). With measurements of the load applied to the thread and its change in diameter during the rolling process values of stress and strain are derived. A stress-strain relationship while the clay is in the fully plastic and ductile state is obtained. From these curves quantitative measures of fully plastic toughness as work per unit volume, with units of kJ/m^3, are derived as the area beneath the curve over a given strain range for specimens prepared over a range of water contents from just below the adhesion limit down to the plastic limit. Tests with water contents below the plastic limit were shown to be non-ductile with no longitudinal extension and broke diametrally in a brittle manner. Because the specimen tested benefits from minimal interference from the operator and minimal restriction in its freedom of movement subtle changes in behaviour can be detected, particularly with respect to its water content.

Good linear relationships between plastic toughness, T and water content, w are obtained. The plastic limit is obtained at the transition between the ductile and brittle states where specimens with water contents within less than a percentage point each side of the transition permit accurate determination of the limit. Because the distinction between plastic or ductile clay and brittle clay can be clearly detected using the apparatus the subjective judgement of a crumbling condition when carrying out the standard manual thread rolling plastic limit test is eliminated. The test also provides the maximum toughness at the plastic limit, and the toughness limit, the water content at zero toughness. The result for the N6 Fireclay is presented in Fig. 1 to show the water content boundaries between the plasticity states, the liquid limit, w_L, toughness limit, w_T, stiffness transition, w_S and the plastic limit w_P at the ductile-brittle transition. With many clays there is a clear break in the gradient of the toughness - water content plot, at the stiffness transition, producing a bilinear relationship. This has allowed the workable region between just below the adhesion limit and the plastic limit to be separated into soft-plastic and stiff-plastic regions. Plasticity states additional to those described by Atterberg can then be identified by this stiffness transition.

The example presented in Fig. 1 is typical of all of the results produced with the apparatus (Barnes, 2013b) with statistical regression of the data points producing good straight bilinear relationships with coefficients of correlation almost always above 0.95. For some of the coarser kaolinite clays the stiffness transition was less distinct with the data points producing a single straight line but with the clay visibly changing gradually from a soft to a stiff condition.

The sticky limit or adhesion limit is not determined directly as there is no recognised method to identify this change of state. With the apparatus a soil thread can only be rolled satisfactorily with unhindered diameter reduction and longitudinal extension providing it does not adhere to the rolling plates. For a clay in a sticky condition unrepresentative higher values of toughness would be obtained because adhesion increases the amount of work required to roll out the clay thread. The test with the highest water content that did not stick to the apparatus plates could be taken to represent the lower limit of adhesion.

2.2. Clay mixtures

Tests were conducted on mixtures of three pairs of clays as follows.

1) Samples of two natural ball clays were obtained of the Creekmoor Clay and the Parkstone Clay from the Dorset, UK works of Imerys Minerals Ltd. The samples were air-dried, crushed and ground to pass through the 425 μm sieve. These samples were chosen to investigate the effects of blending natural raw clays, as conducted in the production of processed clays.
2) Samples of two processed ball clays in powdered form, AT Ball Clay obtained from Bath Potters Supplies Ltd., UK and K-T Ball Clay obtained from the Kentucky-Tennessee Clay Company, USA.
3) Samples of a typical Fireclay, N6 Fireclay obtained from Potclays Ltd., Stoke-on-Trent, UK in moist form and the AT Ball Clay in powdered form. These mixtures were chosen to investigate the effects of adding high plasticity ball clay to the less plastic fireclay. The fireclay was processed as for the natural clays.

Kaolinite is the predominant mineral in all of the clays but the detailed mineralogical composition of the clays was not available.

Mixtures of the two clay powders were prepared in the ratios 0:100, 20:80, 40:60, 60:40, 20:80 and 100:0 and mixed with sufficient distilled water to provide a water content just above the liquid limit. By reconstituting to the liquid limit and curing for at least 24 h it is assumed that the clay particles were sufficiently fully hydrated (Armstrong and Petry, 1986).

3. Results and discussion

3.1. Consistency limits

The tests conducted were the liquid limit to BS1377:1990 followed by the mechanised rolling method using the author's apparatus to determine the plastic limit.

The Atterberg limits (liquid limit and plasticity index) are plotted on the Casagrande plasticity chart in Fig. 2. Most of the points plot above and parallel to the A line, typical of sedimentary clays from temperate regions. Using the plasticity index (or the liquid limit) as a measure of plasticity, the mixtures show variation from low to high plasticity. Casagrande (1947) identified a group of kaolin-type clays derived from the weathering of feldspars in granitic rocks that plotted just below and parallel to the A line. The points for two of the clays, the Creekmoor Clay and the K-T Ball Clay plot just below the A line. Addition of the respective clays takes the points for the mixtures above the A line. Casagrande noted that the toughness of clays near their plastic limits increases with increasing distance above and perpendicular to the A line. This is the case for the mixtures of K-T Ball Clay with the AT Ball Clay but not for the mixtures of Creekmoor Clay and Parkstone Clay.

For the three mixtures the liquid limit, plastic limit, stiffness transition and the toughness limit are plotted in Fig. 3a–c enabling the identification of the adhesive-, soft- and stiff-plastic regions and the brittle region. The plasticity state is seen to be quite sensitive to water content changes, particularly between the soft-plastic and brittle regions.

A simple law of mixtures based on volumetric proportions of two clays A and B for a clay property, such as the liquid limit, can be