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Research paper

What is clay? A new definition of "clay" based on plasticity and its impact on the most widespread soil classification systems

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ABSTRACT

Clays are key elements not only in geological and environmental processes, but also in many human activities. To differentiate clays from other soils, AIPEA and CMS highlight plasticity as the clays' most distinctive characteristic. However, the lack of any reliable plasticity yardstick makes the particle-size-criteria to be more widespread. In a previous work, the authors found some innovative ratios between the plasticity index (PI) and the liquid limit (LL) which allowed the clays' boundary to be established according to a plasticity basis. As plasticity is directly associated with toughness, different published data containing valuable information have been processed in this study by plotting toughness values against PI/LL ratios. In this way, the soundness of the previous authors' finding has been checked. It is demonstrated that a fine-grained material can be defined as a *clay* when PI ≥ LL/2, while a material is *moderately or slightly clayey* if LL/3 < PI < LL/2, such that when PI ≤ LL/3 the influence of clay minerals is much reduced. Apart from an updated classification of soil for engineering purposes, a new textural soil classification is presented, alternative to the USDA one, which allows the real nature of a soil to be known accurately by means of plasticity tests and simple sieving instead of particle-size sedimentation methods.

1. Introduction

Clays are ubiquitous materials whose study as fine-grained rocks and soil components is critical for the understanding of global sedimentary (Środoń, 1999), biological (Pentráková et al., 2013; Yu et al., 2013) and environmental (Singer, 1984) processes. Outside a geological perspective, clays are part of our daily lives to such an extent that their applications are almost limitless due to their particular physical and chemical features. The use of clay by man comes from Prehistory (Wagner et al., 1998; Carretero, 2002) and extends to the present, such that its influence is so enormous that covers fields as diverse as: ceramics (Dondi et al., 2014), construction materials (e.g., Sabir et al., 2001), health (Carretero, 2002), agriculture (USDA, 2017), civil engineering (Casagrande, 1948; Penner and Burn, 1978), environment (Sellin and Leupin, 2013; Uddin, 2017) or chemical industry (Garrido-Ramírez et al., 2010; Nagendrappa, 2011), among many others.

However, what is *clay*? In general, clay-investigation disciplines have relied on particle-size criteria over the years to answer this question, but without reaching any real agreement. Thus, broadly speaking, sedimentologists usually use a particle size < 4 μm (in equivalent spherical diameter, e.s.d.) for clays distinction, while geologists consider 2 μm and colloidal chemists just 1 μm (Guggenheim and Martin, 1995). It is noteworthy that these disagreements are also found in the two most widely used methodologies for measuring the clay content: while the traditional sedimentation tests tend to overestimate the clay percentage, the more sophisticated laser-diffraction methods underestimate it (Buurman et al., 2001; Eshel et al., 2004; Ferro and Mirabile, 2009), which could denote the need to find an alternative approach for clay identification.

Nonetheless, despite the common use of a specific particle size as upper limit to differentiate clays from silts, the AIPEA/CMS definition of clay is against it, stating that the plasticity and the capability to harden when dried or fired are the main characteristics of clays (Guggenheim and Martin, 1995). This plasticity-based definition is also defended in the *Handbook of Clay Science* (Bergaya and Lagaly, 2013). In that book, Bergaya and Lagaly (2013) also express the difficulties to find a consensus between disciplines when defining the term *clay*.

Plasticity is *"the ability of the material to be molded to any shape"* and is provided by the so-called *clay minerals* (Guggenheim and Martin, 1995). According to Bergaya and Lagaly (2013) the term "clay mineral" is also difficult to define, so, as a first approximation, it refers to a class of hydrated phyllosilicates constituting the fine-grained fraction of rocks, sediments and soils. Relying on the AIPEA/CMS definition (Guggenheim and Martin, 1995), clay minerals are those minerals that

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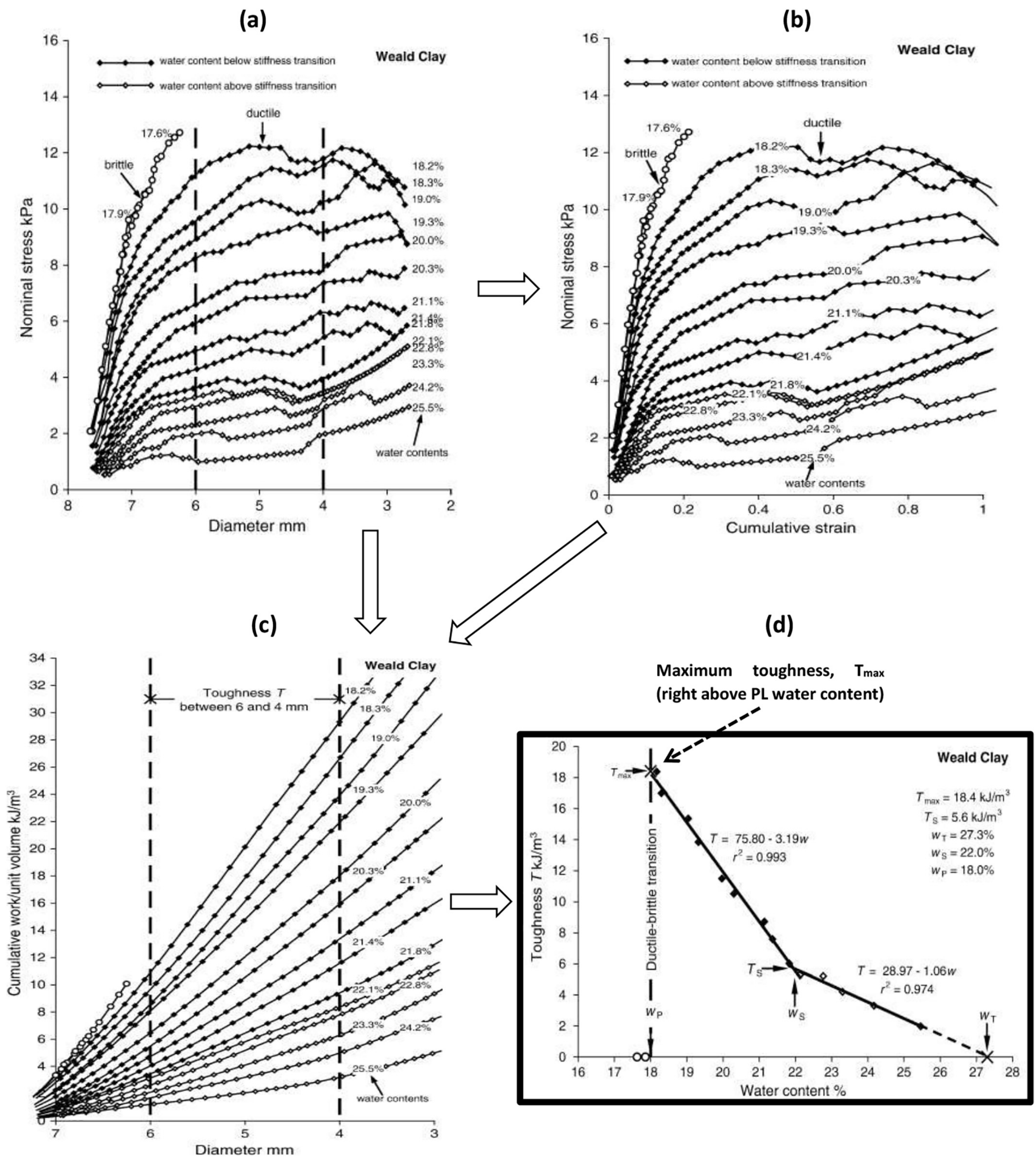

Fig. 1. Graphical sequence for calculating maximum toughness in a clay according to Barnes method (Barnes, 2009, 2013a, 2013b): (a) initial nominal stress-diameter data obtained when clay threads are rolled with the Barnes apparatus; (b) graph obtained after translating original diameter data into cumulative strain; (c) cumulative work per unit volume against diameter, where the former is the product of nominal stress and diametrical strain for a 100 rotations traverse; (d) final relationship between toughness (T) and water content, where T is calculated as the cumulative work per unit volume to reduce the thread diameter from 6 mm to 4 mm, such that maximum toughness (T_{max}) is related to the water content right above the Plastic limit. These figures have been extracted and edited from Barnes (2013a).

are able to impart plasticity to clay and to harden when fired or dried, so that these conditions would be applicable not only to phyllosilicates, but also to other non-phyllosilicate minerals, regardless its individual particle size or origin (Guggenheim and Martin, 1995; Bergaya and Lagaly, 2013). Hence, unlike the conventional definition of clay, requiring a natural origin, clay minerals may be synthetic (Guggenheim and Martin, 1995; Bergaya and Lagaly, 2013). Anyway, clay minerals identification is relatively simple by techniques such as X-ray