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Research paper

Swelling properties of natural and modified bentonites by rheological description

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ABSTRACT

Bentonite is used for landfill application because of its high sealing ability. Following the swelling phenomenon the water reacts with the bentonite and expands the solid particles. The voids are filled and this reduces permeability of the soil. However, the drawback is the long time needed to assess the hydraulic performance, whereas the engineers require simple and rapid characterization parameters to design the hydraulic barrier. Present paper investigates the possibility of use of rheology testing to describe the swelling properties of bentonite used for geotechnical engineering issues. Rheology testing is proposed to investigate the swelling properties of different nature of bentonite. Different types of bentonite are tested: natural sodium, natural calcium and sodium-activated-calcium bentonites. Rheological measurements are performed in steady and dynamic conditions. Free swell and oedometer swell tests are also performed and compared.
A simple model is proposed to unify the output parameters of the liquid-state bentonite from two rheology tests, with the ones obtained from two swelling tests. This approach propose a single parameter: the swelling ratio β that describes the layer of water surrounding the particles based on the aspect ratio of bentonite packed particles. The method highlights the correlation between swelling characteristics and rheological parameters of bentonites. The results of swelling ratio underline distinctly the difference of mineralogy between the groups of bentonites. A linear equation fits the values of β obtained from the two swelling tests and the values of β obtained from the rheology tests, for all bentonites.
Low correlations are observed between the oedometer swelling ratio and the rheology ratio. But, the free swelling ratio is in good agreement with rheological ratio and demonstrates a stronger correlation between the steady state rheology ratio than the dynamic state rheology ratio.

1. Introduction

Geomaterials are defined as natural or enhanced (compacted, blended, etc.) soils designed for engineering applications such as hydraulic barriers (Koch, 2002) where the hydromechanics properties of the soil on site must satisfy to the regulation requirements. Use of high hydraulic performance geomaterials composed of bentonite is an alternative. Bentonite, a high-moisture reactive clay, is applied as soil binder for CCL (Compacted Clay Liner) or as sandwiched material between geotextiles for GCL (Geosynthetic Clay Liners). The bentonite plays the role of water–absorbent, resulting in low permeability of the soil and contaminant stabilisation.

The commercial bentonites are natural or chemical-treated clays (Alther, 1986; Yildiz et al., 1999). Many factors affect the clay behaviour (Van Olphen, 1977), but the bentonite is generally described as Ca bentonite or Na bentonite, depending on the main exchangeable cation (Ca^{2+} or Na^{+} respectively) on the clay surface sites. Gleason et al., 1997 have performed permeability tests on a Ca clay and Na clay and showed that Na clay have lower hydraulic conductivity than Ca clay. The Na^{+} cation induces a higher water uptake than Ca^{2+} cation. Gleason et al. (1997) state that to reach the plastic limit, the Na-bentonite requires more than 500% of water compared to its initial volume, instead of Ca-bentonite which requires only around 100% of water. Internally, this leads to the extension of the clay particle unit and produces the phenomenon commonly known as swelling (Jo et al., 2001; Katsumi et al., 2008; Shackelford et al., 2000). The dispersion of the bentonite particles is an effect of the swelling. As of immediate consequence, the porosity is reduced and the fluid flow path is then restrained. The seepage is reduced (Mitchell, 1977). This permits therefore the correlation between the low permeability of the geomaterials

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and the swelling mechanism of the clay (Norrish and Quirk, 1954; Van Olphen, 1977).

The characterization of the hydraulic performance is an important key for the qualification and optimization of the bentonite, required for the design of the hydraulic barrier system (Koch, 2002). This characterization must be done at laboratory scale prior any site design to ensure the appropriate choice of bentonite. The hydraulic properties are mainly determined with permeability tests carried out with de-aired water as percolating fluid. Those permeability tests usually ran for several months (Katsumi et al., 2008; Razakamanantsoa, 2009) because the hydraulic conductivity of bentonite geomaterials is very low, with values often observed in the range 10^{-9} m/s–10^{-11} m/s (Couradin et al., 2008; Gleason et al., 1997; Katsumi et al., 2008; Razakamanantsoa, 2009; Shackelford et al., 2000).

Considering that the swelling mechanisms are intimately linked to the hydraulic conductivity of clayey soils, investigations on the swelling properties of clay in the laboratory by oedometer tests and free swell tests are therefore legitimate. A strong correlation has yet to be demonstrated to improve the understanding of the relationship between swelling and permeability. These two properties depend on the clay nature, the fluid and the loading conditions (Mitchell, 1977). The engineers' works would be greatly simplified if fast and reliable tests could accurately approach the hydraulic performance of the material and predict the hydraulic conductivity values of the clay (and specifically) bentonite geomaterials.

Plasticity properties of soil determined by Atterberg limit tests are also used as index for soil mechanics parameters (Mitchell, 1977). The plasticity parameter values vary in accordance with the effects of electrolyte fluids and clay mineralogy. Both parameters are thus associated with the change in clay particles interactions (Gleason et al., 1997; Katsumi et al., 2008). However, the preliminary observations made by Razakamanantsoa et al. (2012) with modified bentonites showed divergence from the expected Atterberg test results. The modified bentonite mixtures were too viscous to be rolled in a cylindrical shape as recommended by the standard.

The rheological characterization of clay is extensively used for colloid state materials (Coussot, 2005; Goodwin, 2004; Russel et al., 1989; Van Olphen, 1977). A few recent studies have tried to apply rheology testing to understand and solve geotechnical problems (Ghezzehei and Or, 2001; Markgraf et al., 2006), highlighting its potential application.

For landfill application, the swelling properties of clays via the rheological characterization for hydraulic barrier designing, is not common (Khandal and Tadros, 1988; Paumier et al., 2008). A precise method to link the rheology parameters of bentonite to its swelling properties is still missing.

This paper highlights the possibility to study precisely the swelling mechanism using a complementary, simple and rapid test which is the rheology. It has the advantage of being precise and given qualitative results traduced to swelling parameters. This kind of parameters is very important for landfill designing, giving practical tools for engineers to optimize the design of hydraulic barriers.

The present study focuses on the liquid–solid continuum between colloid liquid-state and solid-state of the bentonite geomaterials. A single parameter deduced from rheology on liquid-state materials is used to understand and describe the swelling properties of different types of bentonite at solid state. The discussion will be based on the proposed parameter, declined in both liquid and solid domains. For that purpose, the swelling will be unified by an unique comparative parameter, interpreted by spheroids model of clay particles. First, the swelling parameter β is calculated with two swelling tests at solid state: oedometer swell test and free swell test. It is then compared to the β calculated with two rheological tests at liquid state (dynamic and steady conditions).

2. Background

A simple model based on the general clay particle fabric is used to describe the clay swelling. The swelling is interpreted by a single value that represents the extension of a fictive layer around the solid particle. This description is illustrated in Fig. 1 and is known to be commonly approached in other works (Larson, 1999; Russel et al., 1989; Tadros, 1996).

The shape of particle is an influential factor to the swelling mechanisms. Therefore, a schematic parameter, namely aspect ratio, is given in order to approach the general mechanism of the swelling. Clay particles are structured as platelets, or groups of platelets (Mitchell, 1977). The shape of clay particle is elongated with high aspect ratio value because its length dimension is much greater than its width dimension. Suspended clay particles pack into group of platelets and remain difficult to be separated into singular particle due to the electrostatic interactions. But the group of platelets are aggregated particles with significant width. Its morphology is of spheroid shape.

Let R be the longitudinal particle radius and r the transversal particle radius. The unitary solid bentonite volume is in Eq. (1):

$$V_b = 4\pi R r^2/3. \tag{1}$$

The bentonite particles adsorb water and swell. A diffuse double layer is formed by ion exchanges around the particle, due to the different charge position (Van Olphen, 1977). Let us associate a fictive water layer, of thickness a, that includes the water mobilized and bound by electrostatic forces to the clay surface. This fictive layer is simply the consequence of the diffuse double layer. The water layer is supposed to be immobile, relatively to the clay particle. For the simplification of the model, the particles are considered to be spread homogenously in the total volume V_T and their size is assumed to be identical and constant. The unitary fictive volume is hence described in Eq. (2):

$$V_p = 4\pi(R+a)(r+a)^2/3. \tag{2}$$

The packing fraction Φ_p represents the clay particle fraction for which the solid particles are packed in the total volume V_T (Eq. (3)):

$$\Phi_p = \Sigma V_b/V_T. \tag{3}$$

The packing fraction Φ_p is function of the particles shape and size. The clay particles occur as platelets, non-spherical forms. Due to the

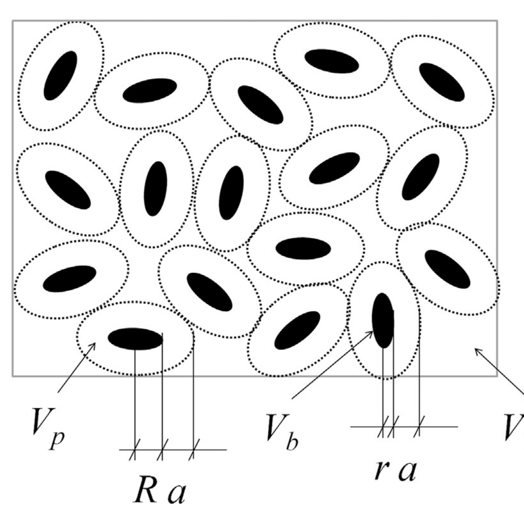

Fig. 1. Scheme of the proposed model of swollen particle configuration, with R the longitudinal particle radius, r the transversal particle radius, V_b the solid bentonite volume of a particle, a the thickness of a fictive water layer, V_T the total volume and V_p the fictive volume of a particle.

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