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A uniaxial cyclic compression method for characterizing the rheological and textural behaviors of mechanically dewatered sewage sludge

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ABSTRACT

The mechanically dewatered sewage sludge with total solid content around 20% on a weight basis is very similar to yield stress fluid, its complex transition between solid and fluid states is not perfectly reversible and especially challenging in terms of pumping, land spreading and drying. To characterize the rheological and textural properties of highly concentrated sludge, a specific methodology based on uniaxial single and cyclic compression tests is developed. Three types of sludge samples (fresh original, fresh premixed and aged original ones) are extruded into cylinders and pressed between two parallel plates using a material testing machine. In single compression, the bioyield point beyond which the sludge fractures is around 7.3 kPa with true strain equal to 0.21. The cyclic compression tests reveal that the sludge behaves as a viscoelastic body when the true strain is smaller than 0.05 and as a visco-elasto-plastic once exceeding the yield stress. The elastic module is around 78 kPa; the viscosity is deduced, in the order of magnitude 10^4–10^5 Pa·s and the yield stress is estimated about 4 kPa. In the unloading phase, the sludge behaves again as a viscoelastic body with clear hysteresis. With the increase of compression speed, the viscosity declines, which confirms that the sludge is a shear-thinning material. The yield stress and the bioyield increase with compression speed, but it does not induce extra internal damage in the samples since the resilience and the cohesiveness are unaltered. The reliability and sensitivity of the method is justified by highlighting the changes of sludge behavior due to aging and premixing effects: both decrease the strain energy density, but do aggravate the adhesiveness of the sludge; the aging makes the sludge less cohesive, while the premixing does not modify its cohesiveness. In spite of changes in test conditions, the elastic module of sludge samples remains unchanged.

1. Introduction

In volume, sewage sludge is the largest by-product recovered in a municipal wastewater treatment plant (WWTP). Typically, these solids and biosolids are in the form of a liquid or semisolid liquid, which contain from 0.25 to 5% of solid by weight. Thickening, conditioning and mechanical dewatering are necessary treatments to remove the moisture, which reduces the volume, improves the handling, facilitates the storage and decreases the transport costs for further valorization. In Europe, most of the municipal WWTPs implement these treatments to best achieve a total solid content (TS) around 18–25% with a continuous dewatering process. Most of the dewatered sludge maintains its shape in the same way as a solid under the effect of gravity but is able to flow like a fluid, i.e. a substance that continuously deforms, when submitted to a high enough stress. These soft materials are very similar to yield stress fluids. But the key difference is that the highly concentrated sludge cannot recover the properties it had before flowing in the liquid regime: the transition between solid and fluid states is not perfectly reversible (Coussot, 2014). Sludge processing, reuse and disposal are among the most complex technical problems facing the engineers in the field of wastewater treatment. This complex transition between solid and fluid states is especially challenging in terms of pumping, land spreading and drying (Baudez et al., 1998). Concurrently, the inevitable impacts of aging (due to the degradation of organic matters) and premixing (including shearing,

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pressing and squeezing induced by pumping, transporting and other mechanical handlings) modify more or less the rheological and textural behaviors of sludge. Papadakis and Bahu (1992) reported the crucial sludge stickiness to equipment surfaces observed in drying processes. The sticking accumulation may lead to significant reduction of dehydration capacity and efficiency (Beckley and Banerjee, 1999; Jing et al., 1999; Kudra, 2003; Ohm et al., 2009). Therefore, the characterization of rheological and textural behaviors of mechanically dewatered sewage sludge is aimed to settle the dominant properties with respect to operational conditions so as to optimize the processing design.

The main factors dominating the sewage sludge properties are the temperature (Lotito and Lotito, 2014; Feng et al., 2014; Dai et al., 2014; Battistoni, 1997; Baroutian et al., 2013; Baudez et al., 2013; Farno et al., 2014; Mori et al., 2006), the composition and the microstructure (Ruiz and Wisniewski, 2008; Lin et al., 2013; Nielsen et al., 1996; Pevere et al., 2009; O'Kelly, 2008; Baudez and Coussot, 2001; Baudez, 2008; Agoda-Tandjawa et al., 2013; Mori et al., 2008; Ma et al., 2014) as well as the solid concentration. Until 2013 (Seyssiecq et al., 2003; Eshtiaghi et al., 2013), most of the rheological characterization studies were focused on sludge from liquid to pasty states (1.5% < TS < 15%). Rheometers have always been the mainstream tool. Unfortunately, an effective standard specifically designed for sludge rheology, that includes both sample preparation and characterization, is lacking. Considering the large number of operating parameters, such as the geometry, gap size, wall surface roughness and pre-shearing rate, it is not possible to get an absolute value for the viscosity (Ratkovich et al., 2013) or the yield stress (Jiang et al., 2014). Few publications are devoted to the characterization of pasty sludge having TS higher than 15%. Jiang et al. (2014) carried out both steady flow and dynamic oscillatory measurements to investigate the impact of solid content and temperature. These measurements were all conducted on a conventional rotating rheometer. At TS around 16%, the sludge was still flowable under tangential stress. The same observation was reported by Agoda-Tandjawa et al. (2013). But for another sludge at TS around 21.5%, Charlou (2014) reported a fracturing phenomenon in a horizontal plane using a parallel plate rheometer in oscillation mode. The shearing test was inadequate to characterize this sludge. However, Battistoni (1997) succeeded in investigating the rheological properties of highly concentrated sludge (up to TS around 33%) with a coaxial cylindrical geometry. But, prior to the rheological test, the sludge was sieved (with a No. 20 U.S. standard sieve of 0.841 mm) and sheared at a shearing rate of 100 s^{-1} for 4 min. These pre-treatments not only irreversibly altered the composition, but also the microstructure of the sludge and the moisture distribution (Liang et al., 2016). Therefore, the rotational rheometers have limited interest when working with mechanically dewatered sludge.

Alternative methods are also reported in the literature. Ruiz and Wisniewski (2008) and Ruiz et al. (2010) adopted the Atterberg Limits, widely applied in civil engineering, to correlate the rheological characteristics of the sludge to its drying and shrinkage aptitudes. O'Kelly (2005, 2006) applied triaxial compression tests, commonly used in soil mechanics, to simulate the mechanical and geotechnical behaviors of solid sludge (TS around 55%) for landfilling purposes. Unfortunately, these methods are not suitable for the purpose of determining the rheological properties of highly concentrated sludge. In other scientific areas, G'sell and Jonas (1979) proposed a tensile testing at constant local true strain rate to determine the plastic behavior of solid polymers with True strain-True stress curves. Ramírez-Wong et al. (1996) used the squeezing flow viscometry technique and the definitions of true strain and true stress to evaluate the rheological properties of fresh corn masa, while S. Sharma and Bhattacharya (2014) adopted this method to show the fracture characteristics of model food gels. These studies share the common features of pasty, gelatinous or solid-like materials and compressing it between two parallel plates to provide an accurate measure of the material behavior during the test. Suitable for application in different fields, universal testing machines (UTM), also know as material testing machines, can perform many standard tests, including single and multiple cycle compression, tensile strength, creep, stress relaxation and resiliency, to describe the deformation behavior and creep properties of materials. UTM have also been marketed to specific sectors with specialized name (texture analyzer for food and top load compression tester for packaging, for instance). Thus, by referring to conventional uniaxial compression tests used for characterizing somewhat similar materials in various fields of research, such as single sludge granules (Lin et al., 2013), gels (Sharma and Bhattacharya, 2014; Yu et al., 2012), sandstones (Zhang et al., 2014) and asphalt mixtures (Cai et al., 2013), we developed an entire methodology - from experiment through modelling and on to simulation - to describe the deformation and flow of a mechanically dewatered sewage sludge (i.e. at TS around 20%) under a given mechanical load.

For the characterization of sludge stickiness, Peeters et al. (2010) and Li et al. (2014) adapted the shearing test used in powder engineering to map the adhesive and cohesive stresses of sludge at increasing solid content. However, these tests only provided sticky strength under shearing. The other textural properties as strain energy density, resilience, energy of adhesion and cohesiveness for energy consumption analysis remained unknown. The lack of these primary elements led us to adopt the entire analysis of texture, also using uniaxial cyclic compression test, developed in food engineering (Steffe, 1996; Hort et al., 1997) for a better understanding of sludge behavior.

The present paper focuses on the experimental methodology only. The objective is first to analyze the rheological and textural behavior of the material, such as elasticity, viscosity, plasticity, hardening index, adhesive and cohesive parameters, under different types of operating conditions. In a second part, particular emphasis is placed on the reliability and sensitivity of this method by highlighting the changes induced by aging and mixing. This methodology is carried out by implementing uniaxial compression, so that it can be applied to sludge behaving as a soft solid with TS between the liquid limit (evaluated by slump test and/or ASTM D 4318 to ensure that the sludge sample can not flow under its own weight by gravity) and the plastic limit (ASTM D 4318 to ensure that it can be considered as a continuous medium).

2. Material and method

2.1. Origin of sewage sludge

The sewage sludge was collected at the WWTP of Albi city in France. Before the biological treatment, the wastewater is screened, de-sanded and de-oiled (Fig. 1). After the extended aeration, a post-treatment removes the nitrogen and the phosphorus from the effluent. The excess sludge is flocculated with a high cationic polymer (BASF Zetag® 8868), thickened and anaerobically digested for six weeks. The digested sludge is flocculated again with a second high cationic polymer (BASF Zetag® 9018) and mechanically dewatered in centrifuges. The material used in this study was sampled at the outlet of centrifugation. Sludge composition was analyzed according to standard EN 12880:2000. The sample ranged in dry matter content from 18.5 to 21 wt%.

As the sludge contains active organic matter, it is necessary to avoid biodegradation phenomena (aging) to have a chance of getting repeatable tests. Storing the sludge in a sealed barrel avoids