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Multistage centrifugation method for determination of filtration and consolidation properties of mineral and biological suspensions using the analytical photocentrifuge

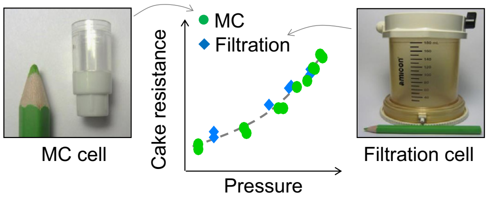
Maksym Loginov*, Nikolaï Lebovka, Eugene Vorobiev

Centre de Recherche de Royallieu, Université de Technologie de Compiègne, BP 20529-50205, Compiègne, France

HIGHLIGHTS

- Filterability was characterized by novel method of multistage centrifugation (MC).
- MC experiments were performed in analytical photocentrifuge.
- Cake dryness, specific resistance and consolidation coefficient were determined by MC.
- These characteristics were determined in a wide pressure range 5×10^3–5×10^5 Pa.
- MC is appropriate for mineral and bio-suspensions and requires only 2 ml of sample.

GRAPHICAL ABSTRACT



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ABSTRACT

The article describes a new method of multistage centrifugation (MC) for determination of filterability (local filtration and consolidation properties) of mineral and biological suspensions. The method comprises centrifugal compression–permeability and sedimentation–consolidation experiments, performed with the help of analytical photocentrifuge at different centrifugal rotation speeds. The experimental procedure implies determination of the analytical centrifugation curves: dependencies of (i) sediment height on centrifugal acceleration in sedimentation–consolidation experiments and (ii) permeate volume and filter cake dryness on centrifugation time and centrifugal acceleration in filtration–consolidation experiments. The combined analysis of these curves yields the pressure dependencies of local cake dryness, specific cake resistance, and consolidation coefficient in the wide range of solid pressure (5×10^3–5×10^5 Pa). Application of MC requires a relatively small quantity of suspension (about 2 ml).

The method was tested for suspensions with different filterabilities and compressibilities: calcium carbonate, kaolin and yeast suspensions. The pressure dependencies of cake dryness, specific cake resistance, and consolidation coefficient, determined by MC, were in correspondence with those determined in the series of conventional constant pressure dead-end filtration–consolidation experiments.

1. Introduction

Optimization of force-driven dewatering of mineral and biological suspensions (e.g., filtration and compression, centrifugal dewatering, gravity settling) requires the knowledge of their permeability and

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* Corresponding author at: Université de Technologie de Compiègne, Unité Transformations Intégrées de la Matière Renouvelable, EA 4297, Centre de Recherches de Royallieu, BP 20529, 60205 Compiègne Cedex, France.

E-mail addresses: maksym.loginov@gmail.com (M. Loginov), lebovka@gmail.com (N. Lebovka), eugene.vorobiev@utc.fr (E. Vorobiev).

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consolidation properties (Fathi-Najafi and Theliander, 1995; Landman and White, 1997; Chan et al., 2003; Barr and White, 2006; Tien and Ramarao, 2008; Mattsson et al., 2012). These properties, namely, dependencies of the solid volume fraction (φ), specific cake resistance (α) and consolidation coefficient (C), on the solid pressure (p_s), should be determined in preliminary experiments for each studied material (Theliander and Fathi-Najafi, 1996; Johansson and Theliander, 2007).

Commonly, the values of φ, α and C are determined in series of dead-end filtration tests or with the help of compression–permeability experiments (in a chamber comprising a cylinder with a piston) (Lu et al., 1998; De Kretser et al., 2001; Teoh et al., 2002, 2006). These methods are well elaborated, but they have some practical restrictions. For instance, it is difficult to characterize the samples in a low pressure region (due to friction between the piston and the cylinder); compression–permeability chamber is not adapted to the experiments with a very small quantity (few milliliters) of suspension; the simultaneous analysis of several samples is difficult to realize.

Centrifugation also may be used as a technique for characterization of suspension filterability and filter cake compressibility. Centrifugal dewatering (sedimentation, filtration and consolidation) was intensively studied and modelled (Valleroy and Maloney, 1960; Hultsch and Wilkesmann, 1977; Sambuichi et al., 1987, 1988; Wakeman, 1994; Green et al., 1996; Smiles, 1999; Chu and Lee, 2001; Chan et al., 2003; Leung, 2004; Barr and White, 2006; Hwang and Chou, 2008; Mota et al., 2008, Iwata and Jami, 2007; Usher et al., 2013; Fukuyama et al., 2013). Several different approaches, based on analysis of the (i) ultimate height of the sediment, (ii) kinetics of centrifugal sedimentation–consolidation (in centrifuge cells with impermeable bottom), and (iii) data of centrifugal filtration (in centrifuge cells with perforated bottom), were proposed.

According to the first approach (i), the local solid concentration φ is determined from the ultimate sediment height dependence on centrifugal acceleration (Murase et al., 1989; Lee et al., 2003; Curvers et al., 2009). The local specific resistance of the sediment α is determined from the equation, relating porosity and permeability of the porous medium (e.g., Kozeny–Carman equation) (Loginov et al., 2011, 2012). Limitation of this approach is related to applicability of the chosen equation to the experimental data (Loginov et al., 2012, Tien and Ramarao, 2013).

Centrifugal sedimentation–consolidation data (ii) can be used for determination of $\alpha(p_s)$ and $C(p_s)$ dependencies (Iritani et al., 1993, 1994, 2007; Loginov et al., 2011, 2012). However, this method is based on hypothesis of sedimentation/consolidation mechanism (e.g., application of Michaels–Bolger, Richardson–Zaki, or Terzaghi–Voigt equations) (Iritani et al., 1993, 1994, 2007; Hwang and Chou, 2006; Iwata and Jami, 2007, Loginov et al., 2012). Moreover, sedimentation–consolidation kinetics can be affected by creep phenomenon (Iwata and Jami, 2007; Loginov et al., 2013), sediment channeling (Holdich and Butt, 1996) and polydispersity of particles (Hwang, 2001; Kochler et al., 2011) that complicate the analysis.

The third approach (iii) requires simultaneous measurement of the filtrate volume, filter cake height, and liquid height above the cake (Sambuichi et al., 1987, 1988; Chu and Lee, 2001, 2002a, 2002b; Hwang et al., 2001; Hwang and Chou, 2006, 2008; Hwang and Chou, 2008; Iwata and Jami, 2007; Fukuyama et al., 2013).This analysis is based on the analytical (Sambuichi et al., 1987, 1988) or numerical (Hwang, 2001; Chu and Lee, 2001, 2002a, 2002b; Hwang et al., 2001; Hwang and Chou, 2006; Hwang and Chou, 2008) solution of centrifugal filtration equation. It can be simplified if the cake properties are determined from the velocity of supernatant permeation through the cake, formed during the initial stage of centrifugal filtration (Sambuichi et al., 1987; Chu and Lee, 2001; Hwang and Chou, 2008).

Despite of successful application of centrifugal filtration for estimation of the local properties of the filter cakes (Sambuichi et al., 1987), this method is rarely used. It can be explained by the rarity of specific centrifugal devices in the laboratory practice.

Recently, a new centrifugal device (so-called, analytical photocentrifuge) was developed (Lerche and Sobisch, 2007). The principle of operation of the photocentrifuge is based on continuous measurement of the space-resolved profiles of light transmission through a sample subjected to centrifugation. The measurement can be performed at different centrifugal rotation speeds. It requires small sample volume (about 2 ml), so, twelve different samples can be studied simultaneously (Lerche and Sobisch, 2007). The analytical centrifuge that was initially developed for characterization of the sedimentation kinetics and determination of the particle size distribution (Lerche and Sobisch, 2007) was further on used for estimation of the local compression–permeability properties of sediments (Iritani et al., 2007; Curvers et al., 2009; Loginov et al., 2011, 2012, 2013, Usher et al., 2013). Iritani et al. (2007) described a method for measurement of the specific resistance of sediment from the initial centrifugal sedimentation velocity in suspensions with different concentrations of particles. Curvers et al. (2009) proposed a numerical algorithm for determination of the pressure dependence of particle concentration in sediment. This algorithm is based on the measurement of ultimate sediment height at different centrifugal rotation speeds. Usher et al. (2013) proposed a method for analysis of the centrifugal sedimentation kinetics and determination of dewaterability (hindered settling function) of concentrated suspensions. Loginov et al. (2011, 2012) proposed an experimental method and different procedures for estimation of sediment characteristics (φ, α, and C) from the sedimentation–consolidation experiments with analytical photocentrifuge. The applicability of this method for analysis of suspensions with different sediment consolidation behavior was also discussed and good correspondence between the values of α, obtained from the analytical centrifugation and dead-end filtration experiments, was demonstrated (Loginov et al., 2013). However, the previous researches (including (Loginov et al., 2013)) did not involve direct filtration–permeation experiments with analytical photocentrifuge. Therefore, they assumed that the characteristics of sediments, formed in a photocentrifuge (φ, α, and C), are similar to the characteristics of filter cakes, formed by filtration.

In this work, a method of multistage centrifugation (MC) is described. It comprises the centrifugal compression–permeability and centrifugal sedimentation–consolidation experiments, made using the analytical photocentrifuge. The centrifugal compression–permeability experiments allowed direct measurement of the cake permeability K and estimation of α without any hypothetical model of the porous medium. Simultaneous determination of $\alpha(\varphi)$ and $\varphi(p_s)$ relations from centrifugal compression–permeability and sedimentation–consolidation experiments permitted obtaining of constitutive equations for $\alpha(p_s)$ and $C(p_s)$.

Another aim of this work was comparison of the pressure dependencies of φ, α and C, determined using MC data, with those obtained from conventional constant pressure filtration–consolidation experiments, and showing of applicability of these dependencies for prediction of the constant pressure filtration–consolidation of mineral and biological suspensions.

2. Materials

The aqueous suspension of calcium carbonate ($CaCO_3$) was provided by OMYA (France). The kaolin suspension was prepared by dispersing the kaolin powder (Société minière des kaolins du Morbihan, Kerbrient, France) in tap water. The yeast suspension was prepared from the powder of dry wine yeast cells Vitilevure