Chemical Engineering Science 93 (2013) 277–291

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Characterisation of dewaterability from equilibrium and transient centrifugation test data

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HIGHLIGHTS

- ▸ Validation of dewaterability characterisation from centrifugal interface heights.
- ▸ Flocculated mineral slurry and biosludge properties used to predict centrifugation.
- ▸ Equilibrium centrifugation used in compressive yield stress algorithm validation.
- ▸ Transient centrifugation predicted to validate new velocity determination method.
- ▸ Data rejection criterion extends transient method applicability beyond gel point.

ARTICLE INFO

Article history:
Received 15 July 2012
Received in revised form
5 February 2013
Accepted 8 February 2013
Available online 22 February 2013

Keywords:
Centrifugation
Particulate processes
Parameter identification
Slurries
Compressive yield stress
Hindered settling function

ABSTRACT

A knowledge of the properties that quantify the rate and extent of particulate suspension dewatering through sedimentation and consolidation is critical to the prediction of dewatering performance for industrial processes such as gravity settling, centrifugation and filtration. The strength of a network of particles in compression is quantified as a compressive yield stress or modulus, $P_y(\phi)$. The rate of dewatering is inversely related to the hindered settling function, $R(\phi)$, which is a measure of hydrodynamic resistance. Dewaterability characterisation over a broad range of solids concentrations is a challenging task requiring tests including batch settling and pressure filtration. Unfortunately, for many systems, these tests are prohibitively slow and an alternative such as centrifugation is useful in accelerating the characterisation. This paper validates algorithms for the characterisation of dewaterability from centrifugal sedimentation data obtained in a laboratory centrifuge with interface height detection and provides guidelines for obtaining accurate results over a broad range of solids concentrations.

Typical dewaterability data for a flocculated industrial mineral slurry and a biological sludge are used as inputs for the numerical prediction of centrifugal sedimentation behaviour. Equilibrium centrifugation at a range of rotation speeds has been simulated and $P_y(\phi)$ data determined using a method described by Buscall and White (1987). The result is shown to be accurate to within 10% of the expected values. Transient centrifugation data has been simulated and $R(\phi)$ determination using a new algorithm is shown to be accurate over a broad range of solids concentrations extending beyond the gel point, provided a new data rejection criterion is utilised. In addition, errors at low concentration in $R(\phi)$ data, caused by dilution, are described. It is shown that currently available analysis techniques are unlikely to quantify these errors.

1. Introduction

Dewaterability describes the rate and extent to which a particulate suspension increases in solids concentration through sedimentation and consolidation in dewatering processes such as gravitational settling, centrifugation and filtration. A knowledge of the properties that quantify dewatering behaviour is critical to the prediction of dewatering performance for such industrial processes. These dewatering properties are highly non-linear as a function of solids concentration and for flocculated suspensions form a continuous particulate network structure that is held together through inter-particle and/or molecular forces at a transition concentration known as the gel point, ϕ_g. It is typical that fine particulate suspensions are flocculated so as to aid the rate of dewatering. The network structure formed at the gel point can transmit stress and in compression, the network resistance

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0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.02.026

to deformation is quantified as a compressive yield stress or modulus, $P_y(\phi)$. The rate of dewatering is inversely related to the hindered settling function, $R(\phi)$, which is a measure of hydrodynamic resistance (Landman and White, 1994). In this dewatering model, the effects of polydispersity are averaged, such that particles and aggregates of different size and density are assumed to move together and not segregate.

Dewaterability characterisation over a broad range of solids concentrations is a challenging task requiring tests including batch settling at low solids concentrations (Kynch, 1952; Lester et al., 2005) and pressure filtration at high solids concentrations (de Kretser et al., 2001; Usher et al., 2001; Stickland et al., 2008). Often, there is a gap between the data obtained from batch sedimentation and that obtained from pressure filtration. In the absence of data, it is usual to interpolate between the sedimentation and filtration data points but this is highly unsatisfactory. An alternative is to bridge the gap using centrifugation characterisation test outputs.

In addition to the above, for many systems, particularly biological sludges such as wastewater sludge, batch settling and pressure filtration tests are prohibitively slow. In batch settling, a small density difference between the particles and the liquid leads to a slow settling rate, requiring a long time to reach equilibrium. Also, for pressure filtration, the sludge forms an extremely impermeable, high solids concentration film at the membrane, through which all liquid must pass, causing extremely slow filtration rates. Decanting centrifugation overcomes both of these issues through an acceleration rate that significantly exceeds that of gravity, achieving higher solids concentrations with no requirement for all of the liquid to pass through a concentrated, impermeable film or cake. Consequently, centrifugation is useful for quicker characterisation of both $P_y(\phi)$ and $R(\phi)$, albeit over a limited concentration range.

To model dewatering processes, the material property data obtained over a broad range of solids concentrations are first fitted to representative constitutive equations or interpolation functions for $P_y(\phi)$ and $R(\phi)$. These functions form the complete solids dependent parameter description inputs to the model. A shortcoming of many commonly used constitutive equations is that they often lack the flexibility required to represent the material properties over a broad range of solids concentrations and, in such situations, a spline or interpolation function overcomes this issue (Usher et al., 2009; van Deventer et al., 2011). Once obtained, these functions can then be used in 1-D models, and pseudo 2-D models accounting for cross-sectional area variations, in order to predict the dewatering performance of tailings impoundments (Usher et al., 2006), gravity thickeners (Usher and Scales, 2005), centrifuges (Burger and Concha, 2001) and pressure filters (Landman and White, 1997; Stickland et al., 2005, 2006).

We introduce here a range of centrifugation characterisation methods available for obtaining both $P_y(\phi)$ and $R(\phi)$ data. The advantages, disadvantages, practicalities and limitations of each method are discussed from the perspective of which methods can be easily applied to produce accurate data. This discussion recommends centrifugation in a flat bottomed tube to equilibrium at a range of rotation speeds to determine $P_y(\phi)$ with data analysis using an easily applied approximate solution (Buscall and White, 1987; Green et al., 1996). Also recommended is a transient centrifugation test at a fixed rotation speed to determine $R(\phi)$ using a generalisation of Kynch (1952) batch settling analysis that accounts for radially dependent centrifugal accelerations. Both of these methods require that the height of the sediment–liquid interface is recorded over the test duration. If necessary, heights can be recorded manually with regular stopping of the centrifuge, but this is not ideal. The height data collection process can be automated using a modified laboratory centrifuge which records light transmission profiles in-situ. These profiles can be accurately converted to transient sediment–liquid interface height versus time data, $h(t)$.

The aim of the work is to theoretically validate a new data analysis method for the calculation of $P_y(\phi)$ and $R(\phi)$ based on automated interface tracking in a centrifuge. Typical material properties for a flocculated industrial mineral slurry and a biological sludge are used as inputs for the numerical prediction of centrifugal sedimentation behaviour. These two systems represent a very large range in dewaterability response, particularly in the hindered settling parameter. Equilibrium centrifugation at a range of rotation speeds is simulated for $P_y(\phi)$ determination. Transient centrifugation data is also simulated for $R(\phi)$ determination. The simulated centrifugation data is used to re-determine the original material properties using the proposed characterisation algorithms. Comparison of the characterisation results with the original material properties enables evaluation of the range of conditions for which the methods are valid.

2. Background

2.1. Compressive yield stress

Centrifugal test methods for characterising the compressive yield stress, $P_y(\phi)$, include equilibrium solids concentration profiling (Bergstrom et al., 1992) or determining the equilibrium sedimentation height variation with rotation speed (Buscall and White, 1987).

The simplest method of equilibrium solids concentration profiling is the scrape test (Miller et al., 1996; Green, 1997; Green and Boger, 1997). The method involves centrifuging a slurry to equilibrium in a flat based tube, removing the sample container, sectioning the sample by height and determining the solids concentration of each section by weight loss on drying. Though this method is nominally simple to employ, it is labour intensive and produces systematic errors due to inaccurate solids concentration determination at the solid-liquid interface.

Utilisation of calibrated light or sub-atomic particle sources and detectors of transmission or scattering can enable profiling of the equilibrium solids concentration profile. Notable sources include gamma-rays (Bergstrom, 1992; Bergstrom et al., 1992) and monochromatic light (Mengual et al., 1999), employed in the latter case by commercial devices such as the LUMiSizer or TurbiScan. Unfortunately, due to the statistical nature of the source and detector system, it is quite difficult to produce reliable and accurate data using gamma-rays. For an inexperienced operator, the resultant data could contain random variability coupled with obscuration near interfaces such as the sediment–liquid interface and the base of the sample container, which make analysis difficult. The detection of transmitted and scattered monochromatic light in the Turbiscan or LUMiSizer can be useful for some materials over a very limited solids concentration range. The accurate solids concentration bounds are determined by the range that can be accurately calibrated, which is limited for most materials because they become opaque at the high solids concentrations observed in networked equilibrium centrifugal sediments. Such light transmission based methods are only likely to be practical and useful for relatively transparent gels and geometries with very thin optical path lengths. Further, the profile is generally recorded when the centrifuge is stationary, causing a number of disturbances to the sample, particularly at the interface, from manual handling and also gravity which acts perpendicular to the centrifugal acceleration. Also, many materials undergo elastic expansion of the compressed network when