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Sedimentation and consolidation of different density aggregates formed by polymer-bridging flocculation

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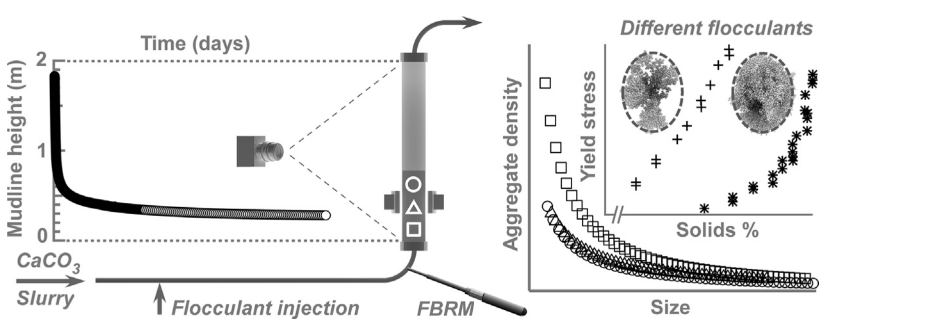
HIGHLIGHTS

- Polymer-bridged aggregates are sensitive to applied shear conditions.
- Sedimentation studies can suffer from poor flocculation control and low data fidelity.
- Flocculation in turbulent pipe flow used to fill wide (190 mm ID) columns.
- Settling mudlines, bed profiles and vane yield stress measured.
- Effect of distinct flocculant chemistries on consolidation is quantified.

GRAPHICAL ABSTRACT



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ABSTRACT

There are numerous models of sedimentation in fine particle suspensions, derived from or validated with physical measurements. Such models could be applied to optimise and control gravity thickeners used for solid-liquid separation in mineral processing. However, these applications rely upon particle bridging by high molecular weight polymers to form large, low density and fragile aggregates. The evolution and refinement of sedimentation modelling for flocculated systems is restricted by a lack of meaningful control of flocculation conditions and inadequate detail in the experimental sedimentation data used for validation.

To address this problem, an experimental system was built to give high fidelity sedimentation data, its use demonstrated for flocculated calcium carbonate suspensions. Turbulent pipe flow flocculation offers tight control of dosage, mean shear rate and reaction time, with aggregate size monitored in-line. The pipe discharges into the base of a wide (190 mm ID) transparent column for which the contents can be isolated, with mudlines then determined from image capture and bed profiles by γ-attenuation. The use of wide columns minimised wall effects that can limit consolidation, while simultaneous efforts to maximise measurement reproducibility and sensitivity led to a greater ability to distinguish subtle impacts from variations in flocculation. Duplicate columns with detachable lower sections enable direct vane yield stress measurement at known bed depths and thereby plots of yield stress vs. solids fraction.

Modelling of such data will be described in subsequent publications, with the present study focusing on key experimental requirements and limitations, the form of data outputs and insights into flocculation impacts. For the latter, off-line determination of individual aggregate settling rate vs. size after bed

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sampling confirmed that higher solids volume fractions low within beds occurred through removal of both inter- and intra-aggregate liquor, i.e. there is a contribution from aggregate densification. Bed profiles and yield stress responses also indicate flocculant functional chemistry can alter how aggregation limits the solids volume fractions attained.

1. Introduction

Solid-liquid separation in the minerals industry often seeks to maximise gravity thickener throughput, i.e. achieving the best solids settling flux by control of flocculation conditions in centre feedwells. Modifying feedwell designs to give better hydrodynamics can greatly alter the size (and thereby settling rates) of the aggregates formed, as can changing flocculant type, dosage and dosing points (Bedell et al., 2015).

The resultant aggregation also affects the thickener underflow solids fraction and rheology. Underflow performance is increasingly targeted in modern thickeners that can deal with beds at higher yield stresses. The permeability (inversely related to hindered settling) and compressibility (related to compaction) are key properties affecting flocculated suspension dewatering, and understanding how measures that capture such properties vary with solids concentration is crucial to modelling thickener performance (Buscall and White, 1987).

There are numerous models seeking to describe sedimentation and consolidation within thickeners, offering predictions of bed heights, bed profiles and underflow concentrations (e.g. Landman et al., 1988; Landman and White, 1994; Bürger et al., 2003; Gmachowski, 2005; Nasser and James, 2007; Li and Stenstrom, 2014). All tend to fail when applied to full-scale applications of polymer-induced flocculation in mineral systems, significantly under-predicting underflow concentrations. This failure can be attributed to several factors:

- Most are based on experimental characterisation of settling for one initial aggregation state (i.e. one initial flocculant dosage and probably only one initial solids fraction). Transient behaviour is then predicted across a wide range of solids fractions, on the flawed premise that aggregation states after flocculation are the same at all initial solids fractions – this is unlikely to be the case for coagulation, and is definitely false for polymer-bridging flocculation, as we have demonstrated (Heath et al., 2006a).
- Bed residence times are measured in hours, and even in the absence of raking, low shear experienced during consolidation leads to aggregate restructuring. Models based on characterising bulk permeability and compressibility solely in terms of solids volume fraction do not incorporate aggregate structural properties or how they change, and therefore cannot be fully predictive (i.e. they represent one characterised flocculation state and cannot predict behaviour for changed flocculation conditions).
- The complex interplay of combined shear and consolidation stress in thickening, particularly when subjected to raking. Aside from a few studies (Gladman et al., 2005, 2010a, 2010b), consolidation and sedimentation under combined shear and compression has received scant attention.

Our long-term goal has been a fully predictive sedimentation model that accounts for changes in initial flocculation conditions and extends this through to impacts on thickener underflows. Ideally, this would also account for rake-induced dewatering, although most likely through the incorporation of sub-models developed in parallel, e.g. refer to aggregate densification studies by Usher et al. (2009) and Spehar et al. (2015).

In seeking to develop a linkage between flocculation and sedimentation models, the need for more advanced experimental characterisation of sedimentation behaviour was recognised. Our earlier work focused on flocculating slurries under tight control of mean shear rates and reaction times, but then only characterised in-line measured aggregate sizes and initial mudline settling rates (Heath et al., 2006a; Owen et al., 2008). There are examples of mudline and bulk permeability/compressibility being measured in detail, but without useful control over the flocculation state (e.g. Galvin and Waters, 1987; Hogg and Bunnaul, 1992; Hunter et al., 2012; MacIver and Pawlik, 2017).

While wall effects are minor in initial stages of low solid settling (Farrow and Swift, 1996), they can be very significant on subsequent consolidation (Lester et al., 2014; Lester and Buscall, 2015). Wall adhesion leads to a limitation in maximum solids volume fraction, regardless of column height, and so ultimately limits the data that can be extracted. Designing suitable testing procedures then becomes a trade-off over multiple factors. Large column diameters offer much reduced wall adhesion impacts, but raise concerns over reliably flocculating large volumes and quantifying performance. The practical convenience and relative ease of quantification with small diameters are negated by wall effects and other complications from a reduced scale. For example, centrifugation can rapidly generate detailed sedimentation data for modelling (Loginov et al., 2011; Usher et al., 2013; Lerche and Sobisch, 2014; Loginov et al. 2017), but exhibits significant errors from meso-scale aggregate structures spanning columns or tubes only ~10 mm wide.

This publication outlines experimental infrastructure developed for continuous controlled flocculation of solid slurries, the subsequent isolation of columns of such solids and accurate characterisation of both mudline settling and final bed profiles. The highest practical frequency of mudline height measurements was sought, as well as the maximum possible depth and solids fraction fidelity during bed profiling. In addition, the option for a detachable column base section enables direct measurement of vane yield stresses on the bed solids at known heights, and from the measured bed profiles the vane yield stress response as a function of solids fraction can then be derived. To our knowledge, no previous study has achieved this level of control over flocculation or detail in mudline settling and bed profile quantification with minimisation of wall effects, thereby allowing more reliable isolation of flocculation impacts.

Such high detail, particularly for mudlines, may be greater than actually required for model development and testing in some of the settling zones, but having detailed datasets serves other purposes. Measurement requirements for routine testing and model application can be elucidated by taking reduced datasets and/or applying synthetic noise. As the phenomenological models for batch sedimentation are well established and validated (Bergström, 1992; Buscall and White, 1987; Chu et al., 2002; Dankers, 2006; Font et al., 1994; Gladman et al., 2010b; Landman and White, 1994; Lester et al., 2005; Usher and Scales, 2005), the majority of uncertainty lies with measurement errors and robust methods to extract and deconvolve material properties from