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Rheology measurements for flotation slurries with high clay contents – A critical review

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ABSTRACT

As a result of the complexity of some ores with high clay contents, rheology is becoming a useful tool to investigate the effect of high viscosities in mineral processing operations including flotation. It has been observed that the presence of clay minerals in flotation slurries has a detrimental effect on concentrate grade and recovery. Concentrate grade is affected by the mechanical entrainment of clay particles that form compact loose aggregates. The detrimental effect on concentrate recovery is mainly caused by cross-linked clay network structures such as the house-of-cards or honeycomb with high pulp viscosity. For flotation slurries, the most common rheology measurements are yield stress and apparent viscosity at different shear rates including the one reported as an average in a flotation cell. The Binghman and Herschel-Bulkley models are frequently used to calculate yield stress by fitting the data from rheograms. Although these measurements are useful, they do not give information about the type of particle associations. In some cases, similar high apparent viscosity or yield stress values do not imply the same effect on the flotation performance since this depends on the type of clay particle associations. In other words, yield stress and apparent viscosity are not enough to predict flotation behaviour of slurries with high clay contents. This review paper recommends some methods for rheology measurements of flotation slurries with high clay contents and proposes that oscillatory rheology be more useful to classify particle associations. This type of rheology measurements is more suitable for slurries with high viscosities. Key information about rheology, clay minerals, and the way they can modify rheology in flotation slurries is also presented.

Contents

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1. Introduction

Rheology is described as the study of flow and deformation behaviour of matter. In general, any external force applied to a body leads to either flow of the body or to a change of its initial shape (Malkin and Isayev, 2006). A body in this context can be any solid, liquid or gas. An ideal solid deforms elastically, meaning that the energy required for the deformation is fully recovered when the stress is removed (Schramm, 2000), and this is called elastic solid. In contrast, ideal liquids and gases deform irreversibly by flowing, the energy required for the deformation cannot be recovered by removing the stress since it is dissipated inside the fluid as liquids and gases flow (Schramm, 2000), and these are viscous fluids. Most solids and liquids have a behaviour between elastic and viscous or what is called viscoelastic behaviour.

Rheology measurements are important in many industrial areas such as paints, polymers, printing inks, paper coatings, ceramics, cosmetics, food systems, pharmaceutical and agrochemical formulation, and liquid detergents (Tadros, 2010). In general, the main goal of rheology measurements in these industrial settings is to maintain the long-term physical stability of formulations or to prevent solids in a suspension or liquid in an emulsion from settling. In mineral processing, rheology measurements are focused on understanding the flow behaviour of slurries since it is very common to handle and process fine ores and concentrates. The properties of these slurries are important in process design, analysis and optimization (Shi and Napier-Munn, 1996a; Klein and Pawlik, 2005), and slurry rheology plays a role in describing the flow behaviour and the resistance to shear or viscosity of the slurry (Shi and Napier-Munn, 1996a). The key part in rheology measurements of mineral slurries is to find what type of measurements is the most appropriate to make and the equipment to use. Klein and Pawlik (2005) reported some of the rheological properties to measure in the design and operation of mineral processes, and from their study it is clear that the type of rheology measurements depends on the operation.

The focus of this review paper is on the rheology of flotation slurries with high clay contents. It is found that the rheology measurement of these slurries is not common in industrial practice. A reason for this is that most flotation slurries with Newtonian nature do not produce rheological problems. However, the continuous depletion of good quality, easy-to-process ores is leading to processing low grade, complex ores which in many cases require fine grinding to achieve mineral liberation and have high clay contents, adding rheological challenges to flotation (Schubert, 2008; Ndlovu et al., 2011). For instance, mixing in the flotation cells can be diminished up to a point where stagnant regions in the slurry are formed as a result of high pulp viscosity. High pulp viscosity can also change the hydrodynamics within the flotation cell, which can negatively affect the various sub-processes necessary for efficient flotation, such as gas dispersion, particle suspension, bubble–particle collision, attachment and detachment (Bakker et al., 2009; Shabalala et al., 2011). At the same time, it is beneficial to process slurries with adequately high solids concentrations in order to reduce water consumption and increase plant throughput, but this increases the slurries' non-Newtonian nature (Bakker et al., 2009).

Proper rheology measurements are critical to correlate rheology with flotation outcomes and to manipulate the rheology of the slurries when necessary. Until now, apparent viscosity and yield stress are the rheology measurements of interest in flotation (Klein and Pawlik, 2005; Forbes et al., 2014; Ndlovu et al., 2014; Cruz et al., 2015b). In this review paper, it is suggested that these measurements may not be enough to predict flotation behaviour given the complexity of clay minerals. Kaolinite, illite and smectite are the most common clay minerals present in coals, heavy mineral ores and base metal sulphide ores (Zbik et al., 2008; Zbik and Frost, 2010). Other examples of clay minerals that are found in other industrial ores are chrysotile, talc, muscovite and vermiculite (Ndlovu et al., 2011). The emphasis of this review paper is on kaolinite (a kaolin) and bentonite (a smectite), a non-swelling and a swelling clay mineral, respectively.

Cruz et al. (2015b) confirmed that clay minerals increased the viscosities of flotation slurries, but similar rheograms for two slurries did not imply similar detrimental effects on flotation. This is due to the effect of different clay particle associations as supported by Cryo-SEM imaging which showed that kaolinite in the slurries formed loose aggregates while bentonite formed more complex structures in the form of a house-of-cards or honeycomb. Apparent viscosities at the reported average shear rate in a flotation cell ($100\ s^{-1}$) or calculation of yield stress by using the Binghman and Herschel-Bulkley models did not give information about the type of network structures present in the slurries. This means that in some cases yield stress and apparent viscosity values alone do not predict the flotation behaviour of slurries with high clay contents. Other rheology measurements may be required to distinguish the type of clay particle associations and correlate it with flotation performance. In this paper, it is proposed that viscoelastic measurements for oscillatory rheology be a useful tool. This type of rheology measurements is more suitable for slurries with high viscosities which are problematic for flotation.

The following sections present some basic information about clay mineral structures and properties with an emphasis on kaolinite and bentonite, the clay particles interactions, fundamental rheology concepts, some common rheology measurements for flotation slurries, the equipment used, and the proposed viscoelastic measurements. It is also discussed how fast settling in slurries can be interpreted in the context of flotation slurries with high clay contents.

2. Clay mineral structures and properties

Clay minerals are anisotropic phyllosilicates that occur in colloidal sizes, and have some special characteristics that differentiate them from regular colloidal particles. They are highly anisometric and often have an irregular particle shape, a broad size distribution, flexibility of layers, different types of charge, a pronounced cation capacity, and disarticulation or delamination (Lagaly and Ziesmer, 2003).

There is no common agreement between different disciplines and professions about the upper size limit for clay particles (Bergaya and Lagaly, 2006). In general, it is proposed that it varies between 1 and 4 μm (Velde, 1995; Lagaly, 2005; Bergaya and Lagaly, 2006). The structure of clay minerals is comprised of one alumina octahedral (O) sheet and one or two silica tetrahedral (T) sheets (TO and TOT layer structures) as shown in Fig. 1. The thickness of the 1:1 (TO) layer and the 2:1 (TOT) layer is about 0.7 nm and 1 nm, respectively. Clay minerals have external basal (planar) and edge surfaces as well as internal (interlayer) surfaces. Most clay minerals have a basal permanent negative charge caused