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Slurry rheology prediction based on hyperspectral characterization models for minerals quantification

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ABSTRACT

The presence of clays in mineral processing offers a number of challenges that range from valuable species recovery to the transport of tailings. In particular, when the abundance of one or more clay types increases, the rheology may be significantly affected. In this paper, the feasibility of using hyperspectral characterization to estimate rheological properties of mineral suspensions was studied. Towards this purpose, a set of rheology measurements was made for slurries of different composition, combining up to three out of five minerals: three clay minerals (two bentonites from different sources and kaolin), quartz and white mica, which are the main gangue minerals present in the Chilean copper mining industry. Using a Bingham Plastic flow model, a set of ternary plots for Bingham viscosity and yield stress was obtained. Results show counter-intuitive behavior for kaolin-white mica mixtures, showing a minimum for viscosity at a 2:3 ratio respectively. In addition, mechanisms for lowering the high viscosity reached by bentonite slurries were assessed. Modelling of the hyperspectral data produced high accuracy estimates of the mineral abundances, enabling an accurate determination of the respective samples position in the ternary mineralogy-rheology diagrams.

1. Introduction

The rheological behavior of slurries is very important in metallurgical processing plants, as it can act as a limiting factor in treatment capacity, due to the fact that at high viscosity and/or yield stress pumps and other equipment may malfunction (Klein and Hallbom, 2002; Kelm and Helle, 2005; Wang et al., 2015; Cruz et al., 2013; Zhang and Peng, 2014). Some mineral mixtures may show unexpected rheological properties (Tan et al., 2013, 2012), such as; sharp rises in viscosity for specific mineralogical compositions, gel formation, time dependency, among others, whose comprehension and prediction may lead to benefits for the process (Bernhardt et al., 1999; Farrokhpay, 2012; Vallar et al., 1999; Nguyen and Boger, 1998).

Rheology in pulps is dominated by physicochemical surface interactions between particles and the fluid (Madigan et al., 2009; Zhou et al., 1999, 2001). Whilst the most abundant components might be expected to have the greatest impact (Johnson et al., 2000), the sensitivity of rheological behavior to surface area can result in specific minerals exerting an influence which is disproportionate with their mass abundance. Clay minerals such as kaolinite and species belonging to the smectite group (e.g. montmorillonite) are often a source of rheological problems due to their common occurrence in metalliferous ores (e.g. porphyry copper deposits (Maksaev et al., 2010; Alpers and Brimhall, 1988) and their intrinsically small particle size/high surface area (MacCarthy and Nosrati, 2013).

Among physicochemical surface interactions, according to DLVO theory (Ninham, 1999), there are two main forces relevant to rheology: electrostatic repulsion/attraction and Van der Waals attraction. The first one exists due to the electrostatic double layer (EDL), which comprises ions adsorbed to a particle surface, creating an energy barrier that prevents other particles of like charge from colliding. This force is very responsive to the concentration and speciation of solutes as well as to the pH of the suspension. On the other hand, Van der Waals attraction is caused by the distortion of the electron cloud as two atoms approach one another, creating a dipole. This force predominates whenever the electrostatic repulsion is weak (Boger, 2000; de Kretser et al., 1998).

DLVO theory has been widely applied to the study of colloidal stability of mineral suspensions. Some authors (Cruz and Peng, 2016) claim that for low slurries with a low proportion of colloidal particles relative to the total solids present, the rheological behavior is mostly explained by the overall solid concentration. In the case of suspensions

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with high clay/colloidal contents the DLVO equation is highly relevant, showing non-Newtonian flow that can have viscous, viscoelastic or elastic response. Moreover, EDL repulsion and Van der Waals attraction effect upon the rheology of clay bearing suspensions has been acknowledged by multiple studies, through the relation observed between the yield stress and the zeta potential due to pH (Goh et al., 2011) and other ions concentrations (Addai-Mensah, 2007).

Previous work (Ndlovu et al., 2014) indicates that suspensions rheology is highly dependent on the specific clay species present in the solid phase. As well, correlation has been found between the clay microstructures and rheological behavior, attributed in some part to the natural shape and charge asymmetry of clay particles (Goh et al., 2011). For example, bentonite slurries which are predominantly smectite in composition, have been reported (Zhang and Peng, 2014; Cruz and Peng, 2016; Zhang et al., 2015; Luckham and Rossi, 1999) to have greater influence on rheological properties when compared to kaolinite-dominated slurries. This has been attributed to the face-edge and edge-edge particles micro-structures, which contrast with kaolinite which tend to form more compact face-face aggregates. Although the precise nature of the physicochemical interactions of clay species is beyond the scope of this investigation, the recognition of the complex interactions involved plays a role in understanding rheological variability in ores and synthetic mineral mixtures.

The present work studies the feasibility of estimating the rheological behavior of slurries from mineral quantification models based on hyperspectral data, which can be obtained at lower cost and time in comparison to other characterization techniques such as XRD, SEM. The ability to anticipate rheological behavior opens the possibility towards developing efficient control systems for slurry holding and transport.

2. Experimental set-up and procedures

2.1. Methodology

Quartz (SiO_2) and white mica were chosen as gangue minerals because they are the main components in the feed of many Chilean metallurgical plants. Bentonite and kaolin were used as sources of montmorillonite and kaolinite, respectively.

Rheology flow curve measurements were conducted at a bulk solids concentration by volume of 30% (54% in weight approx.). Due to the high viscosity and yield stress of one of the bentonites, suspensions were restricted to 15 vol.% (Blakey and James, 2003).

Hyperspectral characterization was carried out using the Hylogger3 (Huntington et al., 2010). The samples were briquettes made from dry duplicates of the samples used for the suspensions. After thorough mixing, the various mineral mixtures received no other treatment aside from pressure before scanning. Several spectral measurements were taken from each sample; some were used for creating models for detecting the presence and the volumetric fraction of each of the five minerals used, others were used for the evaluation of the models.

In order to build all ternary plots, a mixture design (Ayadi et al., 2013) with 13 experiments was selected, as shown in Table 1 and Fig. 1. Considering that the measurements for ternary plots containing the high viscosity bentonite were carried out with 15 vol.% and the rest at 30 vol.%, and the fact that some vertices and edges were common to some triple mixture ternary diagrams, a total of 81 rheology measurements were made.

The density of the samples was determined using pycnometry. Humidity tests were performed to determine moisture contents and the exact amounts of mineral and water to be added when preparing the slurries and the briquettes.

The same mixture design (Table 1 and Fig. 1) was used for the hyperspectral characterization. Finally, using spectral features, mathematical models have been developed for detecting the presence of any of the five minerals, and once detected, another model was applied towards estimating the abundance (volumetric fraction) of that specific mineral in a sample, leading to a point on a ternary plot for viscosity and another for yield stress obtained from a fitted Bingham Plastic Model (Kwak et al., 2005).

Table 1
Mixture design for each ternary plot, A, B and C being any three minerals from the five selected.

Mineral A (vol.%)	Mineral B (vol.%)	Mineral C (vol.%)
100	–	–
67.7	–	33.3
33.3	–	67.7
–	–	100
60	20	20
20	20	60
67.7	33.3	–
33.3	33.3	33.3
–	33.3	67.7
33.3	67.7	–
20	60	20
–	67.7	33.3
–	100	–

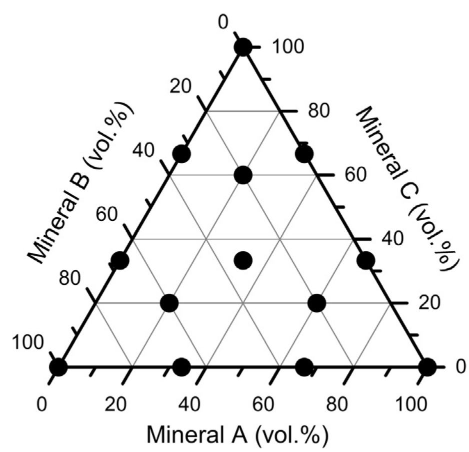

Fig. 1. Mixture design over ternary plot.

2.2. Materials

Five minerals were used for this study: bentonite from a deposit in northern Chile (Bentonite A), COMACSA® bentonite (Bentonite C) COMACSA, 2016, ground COMACSA® white mica, COMACSA® kaolin and finely ground quartz.

Quantitative X-ray diffraction analysis was conducted to determine the mineralogical composition of each material used (Table 3). All XRD data was collected under the same experimental conditions, in the angular range $2^{\circ} < 2\theta < 80^{\circ}$ using Bruker® D8 equipment. These data compared favorably with hyperspectral analysis (see below) of the samples.

To study the particle size distribution, a laser granulometry analysis was performed for every material using Malvern® MasterSizer2000 equipment. These measurements were conducted in a wet environment (distilled water) to replicate their true in-pulp size.

2.3. Preparation of slurries

Slurries were prepared by mixing specific amounts of minerals with distilled and demineralized water. The pH of the synthetic slurries was controlled by adding concentrated sulfuric acid or sodium hydroxide solutions. The corresponding minerals were weighed according to the requirements of each experiment. Subsequently, water was poured into a measuring cylinder. The weighed solids were mixed into the corresponding flask with the water and manually shaken until all solids