A preliminary rheological classification of phyllosilicate group minerals ☆

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A R T I C L E I N F O

A B S T R A C T

With the increased exposure to progressively complex ores, there is growing concern over the effects of phyllosilicate gangue minerals. These minerals present challenges during ore beneficiation, with issues such as reduced flotation performance and complex tailings treatment arising. Often broadly classified as 'clays', the understanding of the distinct behaviour of phyllosilicates remains poor. This work focusses on talc, illite and kaolinite, and forms part of an ongoing study which aims at investigating the entire phyllosilicate group, categorised as serpentine, micas; talc/pyrophillite, kaolinites, illites, smectites and vermiculite. Using pure minerals belonging to each phyllosilicate type, a comprehensive surface charge and rheological analysis was conducted, incorporating their charge anisotropy and non-spherical morphology. The mineralogy was discussed, based on pre-existing knowledge of the minerals. Talc, kaolinite and illite suspensions are characterised by high yield stresses and low viscosities, with differences in their behaviour attributed to variations in charge anisotropy, aspect ratio and surface morphology. A comparison with other phyllosilicates showed that muscovite (mica) results in the least rheologically complex suspensions, while the fibrous nature of chrysotile (serpentine) leads to suspensions with the highest yield stresses and viscosities. The other minerals demonstrate intermediate rheological behaviour. Such a classification may be foundational to geometallurgical advances which can enable process performance predictions based on mineralogy.

1. Introduction

With the rising global demand for minerals and the preferential treatment of higher grade ores in previous years, the mining and minerals processing industries are encountering progressively complex, finely disseminated ores. These ores often require very fine grinding in order to achieve sufficient liberation of the valuable minerals; rendering the recovery expensive given higher energy and capital costs. The processing of these ores is further hindered by the presence of multiple phases of unwanted surrounding phyllosilicate gangue material. Often broadly classified as 'clays', this class of minerals is closely associated with several processing issues such as reduced flotation rates (Ralston and Fornaserio, 2006), complex tailings treatment (de Krester et al., 1997) and pumping challenges (Dunn, 2004). The extensive paragenesis of phyllosilicates from weathering, sedimentation, diagen-

esis and hydrothermal alteration, also means that they are associated with a wide range of host rocks and mineral types. These include volcanic volatile-rich carbonatites (e.g. smectites in kimberlites along the Slave Cratons, Canada) (Boshoff et al., 2007), ultrabasic nickel laterites (e.g. serpentinites in Norseman-Wiluna Greenstone belt, Australia) (Senior and Thomas, 2005) igneous intrusions (e.g. talc in the Bushveld Complex, South Africa) (Schouwstra et al., 2000) and porphyry copper deposits (e.g. micas in Escondida, Chile). Hence, the deleterious effects of phyllosilicate minerals are ubiquitous throughout the minerals processing industry, and an understanding of the specific effects of these minerals on process performance is warranted.

The problems associated with phyllosilicate bearing ores are physicochemical, and impact all facets of the mineral processing circuit, with inefficiencies arising during beneficiation, dewatering and disposal. The 'sticky' nature of phyllosilicates renders the use of conveyors, idlers and screens difficult, and the pump capacity is significantly reduced during materials handling. They also restrict percolation and limit recovery during leaching due to preg robbing (Connelly, 2011a). In comminution, the grinding efficiency is lowered, making it necessary to operate the mill at lower densities (Tangsathitkulchai, 2003). High phyllosilicate ores im-

pede the flotation kinetics, often manifest in higher reagent consumption and poorer selectivity (Schubert and Bischofberger, 1978; Schubert, 2008; Bakker et al., 2009; Shabalala et al., 2011). The risk of wall collapse and leakage is also enhanced during the treatment of high phyllosilicate tailings, resulting from their poor dewaterability (de Kretser and Boger, 1992).

Despite the abundance and adverse effects associated with phyllosilicate minerals, the industry's understanding of the processing issues and potential solutions for treating phyllosilicate bearing ores remains poor. In many cases, these problems are simply avoided by either not processing the ores at all, or by some operations opting to run at significantly lower solids concentrations. Slurry dilution with water is also frequently used to reduce medium viscosity throughout the circuit (Connelly, 2011b). However, this puts a strain on an increasingly scarce resource, particularly given many mines are located in arid or desert regions. Indeed some operations have approached the processing problems by finding chemical and engineering solutions. These include the use of viscosity modifiers such as sodium pyrophosphate (TSPP) and caustic soda, as is done in problematic Merrill Crowe gold plants (Connelly, 2011b). The incorporation of multi-stage cyclones, scrubbers and hydrosizers into the circuit is also used to remove the phyllosilicates upstream (e.g. Mount Keith and Windimurra plants) (Senior and Thomas, 2005). However, such adjustments are not only highly capital intensive, but they are also unsustainable as they may be unable to adapt to variations in ore mineralogy. Other solutions include blending phyllosilicate bearing ores with less problematic ores, but this approach is limited to concentrations below which the phyllosilicate bearing ore starts to cause processing problems. This concentration is strongly dependent on the phyllosilicate gangue minerals present in the ore, and is the concentration beyond which those gangue minerals will cause problems. Such information has not been clearly defined for each phyllosilicate mineral. A better fundamental understanding, particularly of the rheological properties of the different phyllosilicates is required for long-term solutions to these processing problems.

1.1. Rheology in the mineral processing industry

The importance of rheology in different aspects of the processing circuit has been highlighted by several researchers (e.g. Yue and Klein, 2004; Boger, 2009; Farrokhpay, 2012). The rheological properties (simply defined as the suspension yield stress and viscosity) are of great practical importance in many mineral processing applications, as they are useful indicators of the degree of aggregation and dispersion of particles within that suspension (Luckham and Rossi, 1999; Johnson et al., 2000). Although the distinction between these two parameters is often difficult in practice, they each represent different contributions towards overall suspension behaviour. For example, the design and operation of pumping systems of particulate suspensions are based on the viscosity and yield stress values. In such applications, both the yield stress and viscosity will have an impact on energy requirements, with the yield stress having greater significance in ensuring the successful start-up and flow of a pumping system from a static shut down condition (Sofrá and Boger, 2002).

Most studies linking ore mineralogy and their rheological behaviour in the mineral processing industry have been limited to naturally occurring ores; creating an environment that is both difficult to control and quantify, especially when studying the effects of the specific gangue minerals (Wiese et al., 2007; Burdukova et al., 2008; Shabalala et al., 2011). Indeed, there has been an extensive amount of research on the surface charge-rheology relationships of pure phyllosilicate minerals in the geotechnical, soil and colloid science fields, with most studies confined to the clay minerals kaolinite and montmorillonite. As a result, the analysis

of the surface charge properties of these minerals is well documented (Brandenburg and Lagaly, 1988; de Krester et al., 1997; Greene et al., 2002; McFarlane et al., 2005; Tombácz and Szekeres, 2006; Vanerek et al., 2006; Bourg et al., 2007). However, most of these studies have been angled towards other industries (e.g. nanocomposite science, ceramic manufacturing, cosmetics, paper making and soils decontamination), where the key issues are not necessarily relevant within the minerals processing context. Nonetheless, the research already conducted in these industries has demonstrated the importance of the high surface area, asymmetric particle shape, and anisotropic surface charge properties, to the rheological properties of this group of minerals (Rand and Melton, 1977; James and Williams, 1982; Permien and Lagaly, 1994; Johnson et al., 1998; Luckham and Rossi, 1999; Tombácz and Szekeres, 2006). This forms a solid basis for the comprehensive analysis of phyllosilicate mineral rheological behaviour within the minerals processing industry, where to date, the study of these minerals in their pure form is relatively new in its application.

1.2. Phyllosilicate mineralogy

Phyllosilicate minerals are built of varying proportions of tetrahedral (T) and octahedral (O) layers, resulting in minerals of relatively similar structures but with different physical and chemical properties. Consequently, there exist several different classifications and definitions of the group in literature (e.g. Dixon and Weed, 1989; Hurlbut and Sharp, 1998). The classification used in the present work is in accordance with that by Deer et al. (1992), and groups the minerals according to the proportion of T and O layers, as well as the interlayer connections that may occur between successive structural units. This categorises the minerals into serpentinite, talc/pyrophillite, mica, chlorite and clay mineral groups as shown in Fig. 1. The clay minerals can be further classified into non-swelling (kaolinites and illites), and swelling clays (smectites and vermiculites). The rheological properties of suspensions of pure chrysotile (serpentine group), muscovite (mica group) and vermiculite (vermiculites) have previously been investigated, demonstrating their complex flow behaviour relative to a non-phyllosilicate mineral, quartz (Ndlovu et al., 2011a,b). The present study now analyses the illite, talc and kaolinite groups.as part of an ongoing study aimed at characterising the entire phyllosilicate group on the basis of their rheological properties.

Illite exists as a common accessory mineral in many sedimentary rocks, where it is commonly associated with micas and smectites (Klein and Hurlbut, 1993). Studies in the oil sands industry have demonstrated that the addition of illite does not have a significant effect on bitumen recovery (Kasongo et al., 2000). However, it is through its characteristic degradation to smectites, and its occurrence as interstratified illite–smectite that it reduces bitumen recovery (Wallace et al., 2004). Talc is a gangue mineral, commonly encountered in complex sulphide ores and in ores of the platinum group metals (e.g., the Bushveld Merensky, South Africa and the Sudbury Igneous Complex, Canada) (Schouwstra et al., 2000; Holwell et al., 2006; Lotter et al., 2008). In the processing of these ores, the reporting of MgO to the flotation concentrate has been attributed to magnesium bearing minerals such as talc and pyroxene. Being naturally hydrophobic, talc readily reports to the flotation concentrate, effectively increasing the viscosity in the froth phase and altering the froth stability. This results in a reduction in both pay metal grade and recovery. Furthermore, the alteration of pyroxenites to talc often occurs by the formation of talc rims on pyroxene, albeit in minor amounts, enhancing the floatability of pyroxene and increasing the amount of natural flotable gangue (NFG) in the concentrate (Becker et al., 2009). Elevated quantities of talc (and MgO) grades in the concentrate can cause furnace operational problems during smelting and downstream processing.