Minerals Engineering 24 (2011) 594–602

Contents lists available at ScienceDirect

Minerals Engineering

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

Rheological behaviour of lateritic smectite ore slurries

G.K. Das *, N. Kelly, D.M. Muir

AJ Parker Cooperative Research Centre for Integrated Hydrometallurgy Solutions, CSIRO: Minerals Down Under Flagship, CSIRO Process Science and Engineering, PO Box 7229, Karawara, Perth, WA 6152, Australia

ARTICLE INFO

Article history:
Available online 9 September 2010

Keywords:
Nickel laterite
Smectite
Mineralogy
Rheology
Yield stress
Optimum pulp density

ABSTRACT

The characterisation and rheology of several nickel laterite smectite ores and pure minerals are compared to assess the effect of mineralogy and particle size on the viscosity of high pulp density slurries. A vane viscometer was used to determine the "optimum pulp density" (OPD) that gave a yield stress of 100 Pa which is considered to be optimal for pumping slurries into autoclaves in the HPAL process. In general, slurries containing finer particles were more viscous and smectite slurries exhibited poor rheological behaviour as compared to slurries of goethite < kaolin < talc < hematite < maghemite < magnesite. Blending the smectite ores with a fraction of the pure minerals improved the rheological behaviour of the pulp and can increase the optimum pulp density of the smectite blend by over 5% w/w.

When the physical properties of the smectite ore and slurry were examined, a very good linear correlation was obtained between the optimum pulp density and the settling density which provides a simple measure of predicting rheological behaviour of slurries. The variation in the viscosity of the nickel laterite ores depends largely on their mineralogy and particle size distribution. The mean particle size and P_{80} values of various smectite ores containing the same mineral phases were also found to have a reasonably good linear correlation with OPD in saline water, but the correlation of ore surface area with OPD was a poorer fit.

1. Introduction

The indirect beneficiation of nickel laterite ores by increasing pulp density has been recognised as a practical method to improve nickel production in High Pressure Acid Leach (HPAL) plants that are constrained by autoclave capacity and the solids density that can be pumped into the autoclave. By increasing the pulp density of the slurry, a higher nickel through-put from the autoclave is achieved. Slurries with a yield stress of 100 Pa and 200 Pa have the consistency of tomato sauce and toothpaste respectively. McCrabb et al. (2004) have found from pilot modelling studies and plant practice that there would be no issues with pumping a shear thinning slurry into an autoclave at 100 Pa yield stress and this design criteria was used for the Ravensthorpe Nickel Project in Western Australia. Hence the "optimum pulp density" (OPD) is defined as that which gives a yield stress of 100 Pa.

In general, nickel values within laterite ores are associated mainly with the hematite, goethite, serpentine or nontronite minerals – whilst other common minerals in the ores such as maghemite, magnetite, chromite, quartz, talc and dolomite contain very small amounts of nickel. However, since nickel-bearing minerals are finely disseminated throughout most laterite ores, it has been difficult to physically separate and upgrade the nickel content in ores economically, without substantial losses. Muir and Johnson (2006) reviewed several investigations focussing on the separation of these minerals to upgrade the nickel content of the ore using one or more of the following techniques: gravity separation; dense media separation; flotation; magnetic separation; electrostatic separation and sizing. They concluded that the only practical economic option for beneficiating laterite ore is limited to the screening and removal of coarse silica and spinels from the ores; provided the coarse fraction contains little nickel and the overall nickel recovery remains high.

There appears to be little prospect for physically upgrading the clay-like smectite ores by beneficiation based upon size distribution, magnetic separation, flotation, gravity, etc., because of the high nontronite content of the ore, their fine particle size and the suite of other nickel-bearing minerals present. However, it is possible to increase the pulp density of the feed to the autoclave by modifying the rheology and decreasing the viscosity and thereby increase nickel output. Unfortunately, the smectite clay minerals generally demonstrate viscous rheological characteristics. Typically, clay minerals exhibit swelling characteristics, a negative surface charge at neutral pH and the ability to absorb/exchange anions or cations (Grimshaw, 1971).

Several studies have been carried out on various nickel laterite pulps to understand their wide range of viscosity and rheological properties (Avotins et al., 1979; Blakey and James, 2003;

* Corresponding author. Tel.: +61 8 9334 8933; fax: +61 8 9334 8001.
E-mail address: Goutam.Das@csiro.au (G.K. Das).

0892-6875/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mineng.2010.08.011

Bhattacharya et al., 1998; Klein and Hallbom, 2002; McCrabb et al., 2004; Mezei et al., 2002; Sofra et al., 2007). Large differences were even found between the rheology and yield stress of a goethite-rich limonite ore and pure goethite suspensions (James and Blakey, 2004). The rheology literature on concentrated mineral suspensions demonstrates that the viscosity varies significantly with stirring history, the size and shape of the particles (spheres, grains, plates), the length/diameter ratio of rods and fibres; and also with the particle size distribution (Barnes et al., 1993). A reduction in viscosity is even observed with a mixture of small and large particles which is known as the "Farris Effect". However, this effect depends on the fraction of large particles and is optimum with a 50/50 mixture.

The reason why particle size distribution affects the viscosity is attributed to the manner in which particles can settle and pack. It has been recognised that one of the key factors that affects viscosity is the maximum settled density ($C_{v,max}$) or maximum settled concentration ($C_{w,max}$) and how closely the pulp is approaching this value. Clearly, the packing density is influenced by the particle shape and size; and is optimised by having a mixture of small particles that can fit between the voids left by the packing of large particles.

The fundamental relationship between viscosity and settled density is the Krieger–Dougherty equation (Eq. (1)) (Barnes et al., 1993):

$$\eta = \eta_s(1 - [C_v/C_{v,max}])^{-X} \quad (1)$$

where η and η_s are the viscosity of the pulp and solution phase respectively, C_v is the volume concentration of solids, $C_{v,max}$ is the maximum settled volume concentration of the solids, and X is an empirical term that varies according to the shape and size of the particles. For laterite ores this value is about 3.15 (Barnes et al., 1993).

Bhattacharya et al. (1998) considered the Krieger–Dougherty equation in their studies on the rheology of several Indian nickel laterite suspensions but they found that the Bingham viscosity increased exponentially according to the weight fraction of solids and found the following straight line relationship.

$$\log \eta = -0.6 + 2.41 \cdot C_w/C_{w,max} \quad (2)$$

Thus, once the maximum settled concentration was known, the Bingham viscosity could be predicted for different solids concentrations. However, when this equation was used to model yield stress ψ, separate straight lines were obtained for each sample studied and it was found necessary to include a term that included the surface area of the particles S_o and the size for 50% passing d_{50}. The best fitting overall equation relating yield stress was given by:

$$\log \psi = -2.5 + 77.6(d_{50})^{-122} \cdot (C_w/C_{w,max})/S_o \quad (3)$$

Unfortunately, the particle size distribution was not considered, so the equation does not account for changes in viscosity due to the bimodal distribution of particle size, since d_{50} and S_o can be similar for both bimodal and mono-sized particles.

In this work, special attention has been paid to measuring yield stress with respect to pulp density, as it is the fundamental fluid property that determines pumping and pipeline design requirements for transporting viscous slurries. A vane viscometer was used for measuring the yield stress of high solid density pulps as recommended by McCrabb and Chin (2003), McCrabb et al. (2004) and Sofra et al. (2007). This viscometer measures the true yield stress required for the slurry to irreversibly deform and yield, by slowly rotating a 6 blade vane sensor in the slurry. The specific geometry is chosen to ensure that the slip does not occur between the vane and the slurry. Several nickel laterites were characterised according to their mineralogy and particle size distribution and changes in their rheology were measured with different size fractions, with shearing, and when blended with other minerals. Correlations between the rheology and the physical and mineralogical properties of the ores were carried out to provide an understanding of the key factors affecting their rheology and to provide a simple means of predicting the rheological behaviour of other ores.

2. Experimental

2.1. Samples

A total of 19 samples were used in this investigation, of which 18 were ore samples of Western Australian origin and one was a precipitated sample. All the samples were divided into two sets based on the experiments performed for the required information. The first set was used for rheological studies which contained nine different samples that were divided into three groups for easier identification; laterite samples, iron oxide minerals and gangue minerals. The laterite samples were three different smectite ores A, B and C; the iron oxide minerals were relatively pure samples of goethite, maghemite and hematite; and the gangue minerals were talc, magnesite and kaolin. The term gangue is used for the talc, magnesite and kaolin as these minerals were found to occur in the laterite ore body. Smectites A, B and C are referred as Sm-A, Sm-B and Sm-C in the text, tables and figures for easier representation. Goethite and maghemite minerals were generated from a limonitic nickel laterite ore as explained in Section 2.2 and the hematite sample was obtained from the high temperature and pressure precipitation of iron (III) sulphate solution in the autoclave.

The second set of ore samples was comprised of 10 different, mostly smectite laterite ores. These were used for rheology and settling studies to examine the correlation of the rheology measurement with the settled pulp density and the particle size distribution of the samples.

2.2. Sample preparation

The laterite ores from the first set of nine samples were jaw crushed, roll-milled and wet screened to −53 μm in Perth tap water and allowed to settle. Settled undersize was filtered and stored in an airtight bag. Talc, magnesite and kaolin minerals were pulverised and dry sieved to obtain −53 μm size fraction.

Typically two laterite samples of −53 μm size – smectite (Sm-A) and a limonite ore of Bulong deposit in Western Australia – were processed through a wet high intensity magnetic separator (WHIMS) to separate the magnetic fraction such as maghemite and hematite. In this way, a relatively pure smectite sample Sm-C was obtained from Sm-A and samples of goethite and maghemite were obtained from the limonite ore. The WHIMS products were allowed to settle, filtered and stored in the airtight bag.

The second set of 10 laterite samples were ground and wet sieved in saline water to obtain a −500 μm size fraction, then allowed to settle and filtered. Two of these samples were further wet sieved to obtain a −75 μm size fraction. The undersize was stored in an airtight bag for settling studies and rheology measurements.

All the 19 samples were analysed for chemical composition, particle size distribution and mineralogy.

2.3. Instrumental methods

X-ray diffractograms (XRD) were taken to perform the mineralogical analysis of the samples using calcium fluoride as an internal standard. Exactly 10% w/w calcium fluoride was mixed with the sample and ball milled to homogenise the sample before taking