

RHEOLOGICAL ASPECTS OF NICKEL HYDROMETALLURGY

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ABSTRACT

The importance of good rheology testwork and meaningful rheology data is increasingly being recognized by the mining industry, driven to a great extent by the introduction of high pressure acid leaching of nickel laterites in Western Australia. Most metallurgical plants operate under continuous flow mode, and information on the flowability of various process slurries is needed to generate design criteria for mass and energy transfer processes.

This paper covers the areas of rheological investigation that are required for metallurgical processes such as sample characterization, generation of test results, and interpretation of data. The importance of generating base line rheology during the initial stages of a testwork program is stressed, because of the impact of rheology on equipment selection and design for pilot plants.

Examples include rheological characterization of nickel laterite slurry samples at temperatures ranging from ambient to 200°C. Some of these examples illustrate how effective rheological testwork can be when interpreted correctly. Entire ore bodies or isolated slurry streams displaying difficult or complex rheology may be identified readily and the unnecessary expense of high cost testwork avoided. Future directions that rheology testing may take are also discussed, such as process control using online rheology and the opportunity afforded to move in the direction of compact micro-pilot plants.

INTRODUCTION

Rheology, the science of flow and deformation of matter is a well-established discipline with applications in several fields of engineering including mining and metallurgical. Flow behavior impacts energy and mass transfer based unit operations such as mixing, pumping, grinding, heating, and gas transfer. Processes that involve the physical separation of liquids from solids (settling and thickening) and of solids from solids (screening and cycloning) are also slurry-rheology dependent.

Rheological data requirements from the mineral and metallurgical industries consist of flowability assessment and generation of design criteria. A typical example of a rheology driven process is the hydrometallurgical processing of lateritic ores. While the underlying process chemistry of the high temperature (autoclave) acid leaching is relatively well known, the rheological behavior of various laterite ore samples still needs to be understood. Predicting the rheological behavior of most lateritic

ore slurries from first principles is difficult and may carry a significant risk. This creates the need for testing in order to produce reliable rheological data needed to develop design criteria for equipment sizing. As a result, rheology has become an integral part of metallurgical testwork programs for laterite projects. Ore type and orebody variability increase the amount of rheological data needed for adequate characterization of the deposit and subsequent generation of comprehensive design criteria.

This paper provides a general overview of the rheological behavior of various lateritic ore slurries. The information presented was summarized from data generated during commercial testing. Future directions such as impact of rheology knowledge on testwork design, integrated compact pilot plants, high purity materials, and nanorheology are also briefly discussed.

APPLIED RHEOLOGICAL TESTING

The concept of applied rheological testing is common to most process industries, including mining and metallurgy. Important factors that determine the quality of rheological testwork results include:

- Understanding of rheology fundamentals;
- Generation of unambiguous test-data;
- Interpretation of the results and elaboration of design criteria.

Particulate fluid character dictates the most relevant rheological properties pertaining to mineral and metallurgical process slurries. Consistent application in practice of the theory of particulate fluids, in conjunction with adequate testwork procedures allow for the generation of unambiguous rheological test data. The interpretation of the results and design criteria elaboration tend to be more interdisciplinary, in the sense that these aspects are related to both rheology as well as to metallurgical and chemical engineering.

RHEOLOGY TESTWORK

Depending on requirements, various types of viscometers can be used for rheology testwork which is also referred to as rheometry or viscometry. A previous paper [1] discusses aspects related to testwork protocols applied for the generation of rheological data using concentric cylinder rotational viscometry ("CCRV").

The Brookfield viscometer is a fairly popular device for rheological studies, including work on mineral and process slurries. The growing need to test flow behavior at increased shear rates is met by instruments such as those produced by Bohlin, Fann, Haake and other manufacturers. Rheological measurements of unstable slurries often require customized instrument configurations [2]. Similarly, high temperature testing requires special measuring systems, such as the high accuracy Haake RS75 concentric cylinder rotational rheometer that was used to generate most of the data presented in this paper. The equipment features extremely sensitive torque measurement (10⁻⁶ - 10⁻¹ Nm range), high temperature capability, controlled shear/stress modes, and the ability to generate numerous data points with the option for linear or logarithmic collection. Given its high accuracy, the instrument has the potential to minimize most of the errors common to concentric cylinder viscometers [3, 4, 5, 6]. Programming, operation and data reduction are carried out using a proprietary software package. This allows various standard operating protocols to be designed, pre-programmed and carried out, permitting the simulation of various flow regimes

encountered in real unit operations. Despite the fact that instrumentation and measuring technologies are available that allow for accurate and meaningful rheological data generation, some uncertainty and confusion still persists within the industry regarding the reproducibility and applicability of rheological data. It is a distinct objective of this work to present and discuss an approach to rheological testwork that has been proven efficient in providing consistent and practical data.

PARTICULATE FLUIDS

A particulate fluid can be simplistically defined as a system composed of a discontinuous solid phase dispersed in a continuous liquid phase. Assuming uniform distribution of the solids in the liquid phase, the particulate fluid can be considered as pseudo-homogeneous. Provided that settling is sufficiently slow, these fluids are generally considered to be "non-settling" or "stable" (particulate) systems.

Particulate fluids of specific interest in mineral and metallurgical processes are commonly known as "slurries" or "pulpes". These fluids can be subdivided into three main types: "Non-Flocculated" ("Deflocculated"; or "Fully dispersed"), "Flocculated"; and "Fibrous" [3, 4].

In a broader sense, the rheological behavior of the slurries is determined by physical and physico-chemical factors [3, 4, 7, 8, 9]. Physical factors include temperature, shearing-induced hydrodynamic (liquid-particle) interactions, as well as properties related to the suspended particles, such as their shape, concentration, size and size distribution.

Physico-chemical factors consist of attractive and repulsive interactions between the particles. Attractive interactions include Van der Waals, long range electrostatic and hydrophobic forces. Repulsive interactions consist mainly of Van der Waals, hard sphere, as well as short and long range (double layer) electrostatic forces. The Van der Waals forces tend to act as attractive forces, except when the solid particles are composed of dissimilar materials

suspended in a fluid of intermediate density, such as in the case of particle-bubble interactions in water [7].

The zeta potential is a measure of the net result of the attractive and repulsive inter-particle forces. The value of the zeta potential indicates whether the particles adhere on collision or remain in a dispersed state.

A non-flocculated or partly deflocculated, low particle concentration slurry (i.e. particulate fluid) tends to follow what is referred to as Newtonian behavior, characterized by a unique value of the viscosity, η , that is independent of the rate of shearing to which that fluid is being subjected [3, 4, 5]:

$\eta = \tau/\dot{\gamma} = \text{constant}$, where τ is the shear stress and $\dot{\gamma}$ is the shear rate.

In these low volume fraction, "ideal" particulate fluids, the correlation between viscosity and solids density tends to obey the Einstein relation [3,4,7,8].

$\eta = \eta_0(1+2.5\Phi)$ where η and η_0 are the viscosities at volume fractions Φ and $\Phi=0$, respectively.

In the above situation, individual particles (or relatively small aggregates) act as flow units. At intermediate solids concentrations, the flow units tend to become increasingly larger, as a transition towards the flocculated state takes place. Variable shearing of medium to high intensity may induce dilatant ("shear thickening") behavior in these slurries, causing an increase of viscosity.

In mineral and metallurgical processes, high volume fraction particulate fluids that can be assimilated to relatively stable flocculated systems are common. Under gradually increased shearing, the flocs are reduced in size, progressively releasing some of the liquid component, making it available as medium ("lubricant") for the motion of the particles. The net (measurable) effect is a reduction of the resistance to flow (i.e. viscosity) of the slurry. This phenomenon is known as shear thinning. Shear thinning is characteristic for Pseudoplastic fluids. Further shearing

at constant rates, for a certain period of time, can produce a thixotropic breakdown. Thixotropy is the condition whereby the flowability of a particulate fluid increases due to shearing in time. Rheopexy (anti-thixotropy) is the opposite phenomenon, consisting of a build-up of the resistance to flow of a particulate fluid due to shearing in time.

Time-dependency of the viscosity of mineral slurries is in general of a transient nature, as it usually reflects the time required for the fluid to reach a constant viscosity value (i.e. flowability).

Being shear rate dependent, the flocculated particulate fluids do not follow Newtonian flow behavior and the relationship between viscosity and solids density cannot be expressed by the Einstein equation.

Their inherent settling tendency renders most of the mineral and metallurgical process slurries as quasi-stable systems. Most of these materials will not flow unless a stress that exceeds a certain value, the yield stress, is applied through shearing. This is known as Bingham Plastic behavior and is widely encountered in the study of the particulate fluids. The yield phenomenon separates the quasi-solid and quasi-liquid states of the Bingham Plastic particulate fluids. The behaviour of Bingham plastic fluids tends to be time-dependent to a certain degree (i.e. until they reach their ultimate flowability), since their shearing history generally influences their rheology.

It should be noted within the context of this brief overview that in strict theoretical terms, time-dependent fluids cannot be characterized by non-Newtonian rheology. Time-dependency may exist as thixotropy, or rheopexy (anti-thixotropy). A widely accepted practical compromise however takes into account the fact that in general, both thixotropy and rheopexy are transient phenomena. Accordingly, most mineral slurries tend to reach a final (i.e. "equilibrium" or "ultimate") value of their flowability at which point a non-Newtonian assessment of their behavior can be made and used for engineering purposes.

Furthermore, in terms of settling behavior, "ideal" particulate fluids, characterized by lack of interparticle interactions, obey the Stokes relation [10]:

$$V = 2 gr^2(\rho_1 - \rho_2)/(9\eta)$$

where V is the final settling velocity, g the gravitational constant, r the particle (assimilated to a sphere) radius, ρ_1 the specific gravity of the particle, ρ_2 the specific gravity of the liquid and η the viscosity of the liquid.

This equation can be used for quantitative predictions only for the individual particle settling regime. Its applicability is limited in general by factors such as hindered settling and agglomeration, phenomena occurring in more advanced stages of the settling-thickening processes, such as flocculation-clarification, zone settling and compression [10]. Predicting settling conditions under these conditions is complicated and generally limited to solids volume fractions of 0.4 or less. The settling velocity decreases, tending to zero as the maximum attainable solids density is approached. The hydraulic forces do not dictate the settling behavior under these conditions. Instead, the determining factor consists of the mechanical resistance of the settled solids. The rheological parameter of relevance for ultimate dewatering in this situation is the compressive yield stress [9].

Fibrous slurries are found less often in mineral and metallurgical processes. They contain long, flexible fiber shaped particles, which tend to form flocculated structures even at very low volume fractions. Therefore, non-Newtonian flow behavior is common in the case of dilute fibrous slurries. However, the suspending medium is easily displaced from the fiber-flocs, causing sudden changes of rheology. These changes tend to be difficult to track experimentally, due to the development of non-uniform particle concentration profiles in the mass of the entire fluid and/or at its boundaries (i.e. wall-slip).

RHEOLOGICAL MODELING

Rheological modeling of particulate systems is based on experimental flowcurves generated by test data. Regression analysis is the most common mathematical tool for data interpretation as it allows for the characterization of rheological compartment over certain selected shear rate ranges, as required by the application. The equations for the most prevalent laminar flow models [3, 4, 5, 11, 12] illustrated in Figure 1 are:

Newtonian	$\tau = \eta \dot{\gamma}$
Bingham Plastic	$\tau = \tau_y + \eta_P \dot{\gamma}$
Ostwald-de Waele Power Law	$\tau = K \dot{\gamma}^n$
Herschel-Bulkley or Generalized Bingham Plastic	$\tau = \tau_y + K \dot{\gamma}^n$

Examples of models that describe more complex rheological behavior include:

Casson $\tau^{0.5} = \tau_y^{0.5} + K \dot{\gamma}^{0.5}$

Oka's Unified Model

$$d\tau/((\tau+a)^m) = k d\dot{\gamma}/((\dot{\gamma}+b)^m)$$

where τ and $\dot{\gamma}$ are the shear stress and shear rate respectively, τ_y is the yield stress, η_P is the Plastic (Bingham) viscosity, K is the consistency coefficient and n is the flow behavior index. In the case of the Oka model, a, b, k and m are material constants, which together with the integration constant make that model a five-constant equation.

Models involving the power index n can reflect both pseudoplastic (shear thinning) and dilatant (shear thickening) behavior, corresponding to $n < 1$ or $n > 1$, respectively. The consistency coefficient k quantifies the resistance to flow in the case of those models.

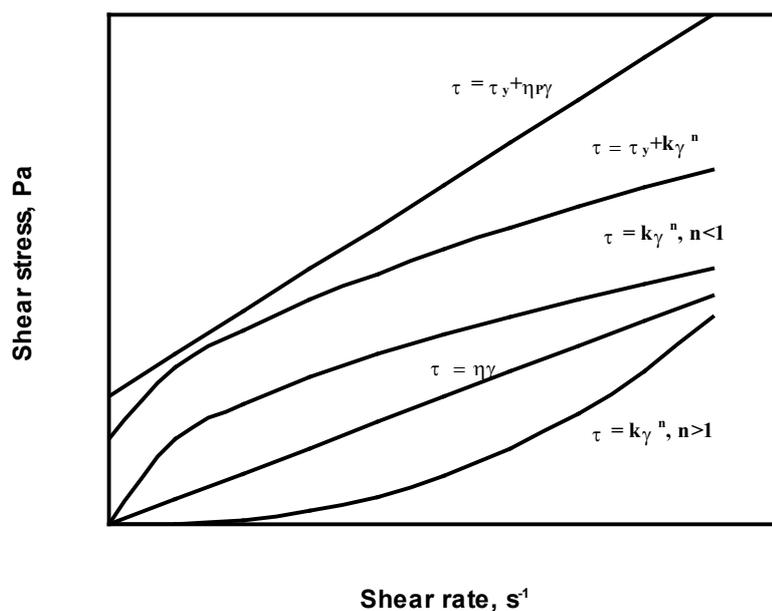


Figure 1 Prevalent Flow Models

The experimental flow curves do not always correspond to the behavior predicted by specific rheological models. In fact, the flow behavior of real slurries can be complex and often displays a “multi-model” tendency. From an engineering point of view, it is important to ensure that a given model reflects the shear rate range of relevance to the unit operation and equipment for which the design criteria would be generated, based on the underlying rheological data. Secondly, it has been confirmed by several practical examples that valid design criteria could be generated based on stable, time-independent values of the rheological parameters, corresponding to conditions of constant flowability. Besides providing practical values, this approach also ensures a reasonable compliance with the theory, according to which, true non-Newtonian rheological models are based on time-independent flow behavior.

Conversely, if a slurry sample follows a highly time-dependent behavior, its flow properties should be treated primarily as a function of its shear history. The application of a suitable time-independent model would be pursued once proven that flowability has reached an unchanged state in time, under a constant shearing regime that replicates as closely as possible the real process conditions.

LATERITIC ORE SLURRIES

The influence of slurry flow properties in nickel laterite processing is perhaps the most relevant example of a rheology-driven metallurgical process.

Lateritic ores (“laterites”) are developed by the weathering of various nickel-bearing parent rocks, and are widely distributed in tropical areas. Lateritic ores consist in general of goethite along with variable amounts of minerals such as serpentine, garnierite, chlorite, olivine, diopside, chromite, vermiculite and others. Laterites with high-aluminum and low-magnesia content are generally known as limonitic, whereas the low-aluminum and high magnesia content ores are commonly identified as saprolitic.

The overall nickel grade in commercially exploited limonitic-lateritic ores ranges from 0.9 to 1.2% Ni; cobalt grade is generally about one tenth that of nickel. The rheological properties of laterite slurries have been intensively studied over the past few years [13, 14, 15, 16]. The rheological behavior of laterite ores greatly influences the viability of any project involving these raw materials. The main technical challenges relate to the (i) flowability of laterite slurries during long distance pipeline transport, (ii) liquid-solid separation processes, (iii) indirect heat

exchange processes and equipment design and (iv) high temperature (250°C) sulfuric acid leaching. Rheological behavior may also be an important parameter in downstream aqueous processing. Technical challenges in this area include purification and separation processes such as pre-neutralization, nickel-cobalt mixed hydroxide precipitation, and subsequent re-leaching unit operations.

LATERITE SLURRY SAMPLE CHARACTERIZATION

As in any testwork technique, accurate sample definition and characterization is critical for generation of quality rheology data. It is often assumed that the slurry sample tested is “ideal” or at least “near ideal”. However, this assumption is correct only in the case of chemically inert aqueous suspensions of (assumed) spherical particles such as sand or flotation concentrates and tailings. This situation is widely encountered in the traditional practice of mineral and metallurgical processing. However, a totally different situation exists when inter-particle and solvent-particle interactions occur, as is often the case with laterites. Examples include various ore slurries and their downstream processing products, such as fine size fraction intermediates, or various precipitates.

A typical example of deviation of the actual specific gravity (ASG) of the solids in slurry from the specific gravity (SG) of the dried solids, in the case of beneficiated laterite slurry, is illustrated in Figure 2.

In our experience, ASG can differ from SG by as much as 40% in the case of limonitic laterite slurries and 60% in the case of certain intermediate process slurries. From both rheological and metallurgical perspectives, it is very important to determine the correct amount of solid matter contained in a slurry sample that is being retrieved from a process, and which is destined for rheological measurements and chemical analyses.

The approach selected was to quantify the degree of cumulative interactions occurring in the slurry, regarded as a

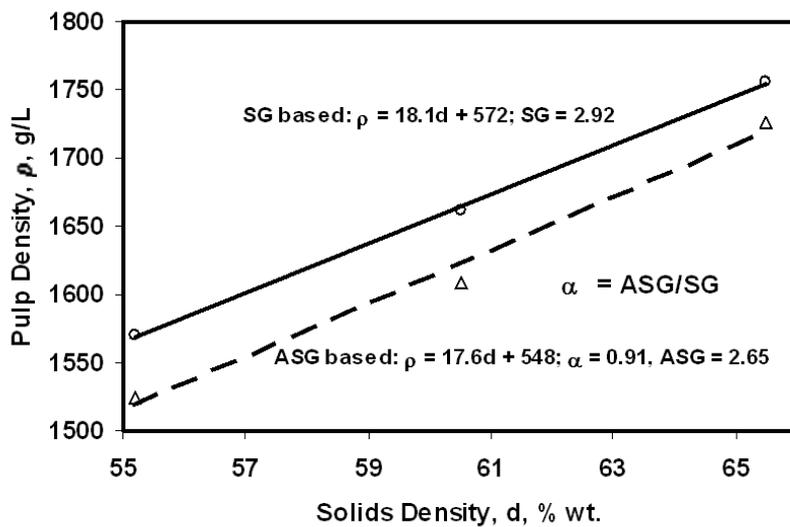


Figure 2 Actual Solids Density Deviation – Laterite Ore Slurry

particulate fluid. It has been found that in order to achieve the required level of accuracy, it was necessary to amend the equation of the ideal mixture to reflect the properties of the real slurry, as discussed below.

For the case of an ideal bi-component particulate fluid, composed of a continuous liquid phase and a dispersed solid phase, the volume of that slurry-system can be expressed as the sum of the volumes of the two immiscible phases, according to the Ideal Mixtures Law [17]:

$$V_1 + V_2 = V$$

where V_1 is the volume of the solid-in-slurry component (flow unit, floc, etc), V_2 the volume of the liquid.

For the case of non-ideal slurry, the above relation can be rewritten as:

$$\alpha V_1 + \beta V_2 = V$$

where α is the correction factor that quantifies the effect of all interactions at equilibrium (i.e. interparticle and solvent-particle) that affect the volume of the “quasi-solid” phase. Correction factor β quantifies the effect of all interactions (i.e. solvent-particle) that may affect the volume of the liquid phase.

By definition:

$$\alpha = ASG/\rho_1$$

where ASG is the “Actual Specific Gravity” and ρ_1 the dry residue specific gravity. In the case of flocculated slurry, the ASG (“Actual Specific Gravity of the Solids in Slurry”) can be formally assimilated to the real density of the “quasi-solid” flow units (flocs) present in the slurry.

The final form of the amended equation can be obtained after substitutions and regrouping:

$$\rho = \rho_1 \rho_2 / (\alpha f \rho + \beta \rho_1 (1-f))$$

where ρ is the pulp density, ρ_2 the solution density in g/L, f is the solids weight fraction of the slurry.

Since pulp density and solids weight fraction are easily determinable, they allow for subsequent calculation of the ASG and implicitly of the α values. In the case of a given process slurry sample, the density of its liquid phase is a constant that includes the effect of any possible particle-solvent (chemical) interaction, such as swelling, ion exchange, etc. Therefore, provided that no interactions occur during sampling (i.e. slurry make-up, post reaction, etc.), the density of the liquid can be determined unambiguously, hence $\beta = 1$. Situations involving $\beta \neq 1$ tend to be more complex, as they may involve the necessity of introducing time as a parameter.

Under the conditions outlined above ($\beta=1$) and, in addition when $\alpha = 1$ (thus $ASG = \rho_1$), the equation reflects the particular case of an ideal mixture, characterized by the absence of any interactions, hence allowing for individual particle volumes additivity. In this particular case, the pulp density can be calculated using the traditional, ideal equation:

$$\rho = \rho_1 \rho_2 / (f \rho_2 + \rho_1 (1-f))$$

For situations when $\alpha \neq 1$, only the ASG values or, alternatively, calibration curves (pulp versus solids fraction functions, $\rho = F(f)$) can be used for accurate pulp density determinations. In either case, the solids density ranges of applicability need to be defined, as some of the interactions (e.g. flocculation), could be influenced by the solids density. Thus the $\rho = F(f)$ relationship may not always be linear. As noted above, the assumption of $\beta = 1$ implies constant solution density for this scenario. Otherwise, α would become a function of time, and its quantification would require kinetic data. The data in Table 1 illustrate the case for beneficiated ore slurry and intermediate process slurry samples originating from a deposit of dry lateritic nickel ore (also mentioned below as laterite type “M”).

In case of beneficiated slurry samples “M13A”, the correction factor α ranged from 0.64 to 0.85, varying in direct proportion to the solids density. Thus, the actual specific gravity of the solid phase contained in those slurry samples was from 16 to 36% less than the dried solids specific gravity. A similar pattern was observed in the case of beneficiated slurry samples “M13B”, although within a narrower range: from 0.73 to 0.77, hence corresponding to a specific gravity deviation ranging from 23 to 27%.

The differences between zones 13A and 13B illustrate the variations that can occur within the same ore body, and highlight the importance of individual sample characterization. The autoclave discharge (ACD), counter-current-decantation (CCD) and neutralization (NTR) process slurry samples referred to in Table 1 are examples of chemically active slurries, hence both α and/or β may vary in time, including during

Table 1 Examples of Slurry Characterization Data - Ore Deposit Type "M"

	*SG	*ASG	β	α	*Density	Solids	
Type					g/L	%	
Sample M13A	4.28	3.63	1	0.85	1480	44.9	
Sample M13A		3.44		0.80	1385	39.0	
Sample M13A		2.73		0.64	1241	30.8	
Sample M13B	4.53	3.49	1	0.77	1479	45.6	
Sample M13B		3.35		0.74	1400	40.9	
Sample M13B		3.30		0.73	1364	38.5	
Typical ACD	3.99	1.60	$\neq 1$	0.40	1301	30.1	
Typical CCD	3.78	2.85	$\neq 1$	0.75	1477	47.1	
Typical NTR	2.66	1.99	$\neq 1$	0.75	1248	36.9	

Notes:
 Slurry samples "M13A" and "M13B" were samples produced from an ore type "M".
 ACD, CCD, NTR: Autoclave Discharge, CCD and Neutralization underflow samples.
 SG: dried solids specific gravity; Density: measured slurry (pulp) density.
 ASG: apparent solids specific gravity, calculated from measured slurry density; $\alpha = ASG/SG$.

sample preparation. When the process conditions allow (i.e. at steady state), quasi-stable slurry-sampling may be carried out. In such a situation, these samples would be characterized by a well-defined β value, preferably near 1.

The chemical changes occurring in the case of acidic slurries (such as ACD) include post-precipitation of iron and silica. The result is a direct change of the weight of the solid contained in the slurry. Since β is not 1 for these systems, the procedure of sample retrieval applied for this type of slurry needs to include progress (kinetic) sampling at regular time intervals and under constant process conditions. The relatively stable autoclave discharge slurry sample ($\beta \sim 1$) displayed the greatest deviation of the actual solid phase specific gravity: 60% below the specific gravity of the dried solids ($\alpha = 0.4$). The chemical changes occurring in the case of precipitated products (i.e. CCD, NTR) include crystallization, hydration/dehydration and aging. These phenomena tend to change the amount of free water in the system continuously, rendering these slurries chemically unstable. Consequently, the solids content (i.e. "solids density % by weight") of these slurries changes indirectly, due to the exchange of water with the liquid phase. The average specific gravity of the solid phase contained in the neutralization slurry samples (NTR) tested was 25% less than the dried solids specific gravity ($\alpha \sim 0.75$).

Figure 3 illustrates the dependency of specific gravity and Bingham yield stress on the solids density for the case of a relatively stable ($\beta \sim 1$) process slurry (CCD) sample. The value of the specific gravity of the solid flow units (material) contained by the slurry is given by the value of the actual specific gravity (ASG). The value of the specific gravity, corresponding to 100% solids corresponds to the specific gravity of the dry solids, determined in nitrogen gas. The significance of the relationship between these parameters can be summarized as follows:

- The actual specific gravity of the solids (ASG), contained in the laterite process slurry sample tested was not constant;
- The value of the specific gravity of the dry solids (SG) was intermediate between two extreme values of the actual specific gravity (ASG), which varied with the solids density of the slurry.
- The minimum ASG value corresponded to relatively dilute slurry. The maximum ASG value corresponded to a solids density approaching the packing solids density;
- The solids density where the inflection point in ASG occurred was also characterized by a sudden increase in the Bingham yield stress, signaling a transition to the quasi-solid state of the slurry;
- In light of the above observations, it is evident that ASG could be defined physically as a unique parameter only in conjunction with its relationship to the solids density of the slurry.

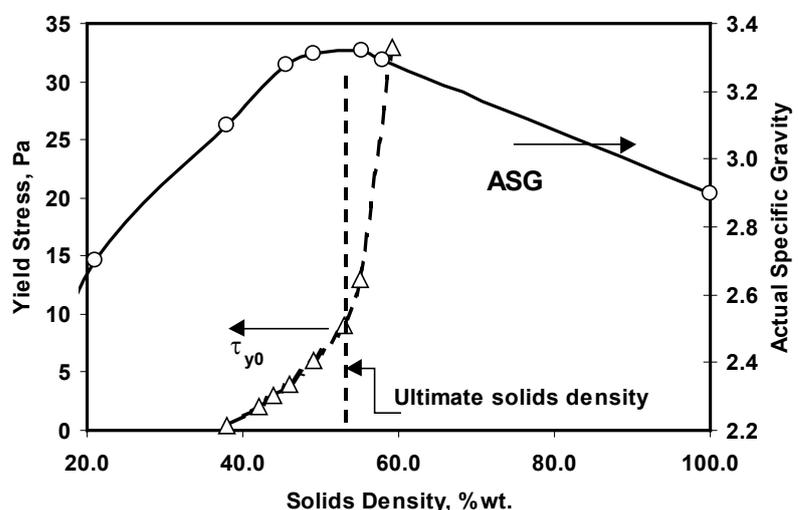


Figure 3 Specific Gravity and Bingham Yield versus Solids Density - CCD Slurries

INTERPRETATION OF LATERITE SLURRY RHEOLOGICAL DATA

Subjecting well-characterized slurry samples to simulated flow conditions allows for the generation of reliable rheological data. This is typically done by determining the variation in yield stress as a function of the rate of shearing. The graphical illustration of such a dependency is called a flowcurve. When apparent viscosity values are plotted instead of the shear stress, the resulting curve is called a rheogram. Non-Newtonian systems such as laterite slurries tend to be more appropriately characterized through the use of flowcurves, such as the one depicted in Figure 4.

The degree of time-dependency at any shear rate is illustrated by the hysteresis domain between the “Up” (increasing shear rate curves) and “Down” (decreasing shear rate curves). The degree of time-dependency in terms of sample shearing history is illustrated by the difference between the “Unsheared” and “Sheared” flowcurves. These flowcurves are produced before and after a prolonged period of constant shearing, which allows the system to reach its equilibrium shear stress or flowability. A typical example of this behaviour, involving a limited thixotropic characteristic is illustrated in Figure 5.

Further rheological data assessment includes the selection of the most appropriate model, which accurately characterizes the flow behavior of the slurry sample tested, according to the principles outlined above. The objective is to provide design criteria and the example provided is related to a slurry transport application. The approach described below is applicable to other rheology dependent unit operations.

Defining the optimum pumping conditions for slurry transport is a typical rheological testwork objective that provides direct design criteria. Examples include pumping of high-density, beneficiated laterite ore slurries as well as process intermediates and tailings. Rheological testwork data generated time-independent flowcurves such as illustrated by the lower (“Down”) curve are illustrated in Figure 6. At least two

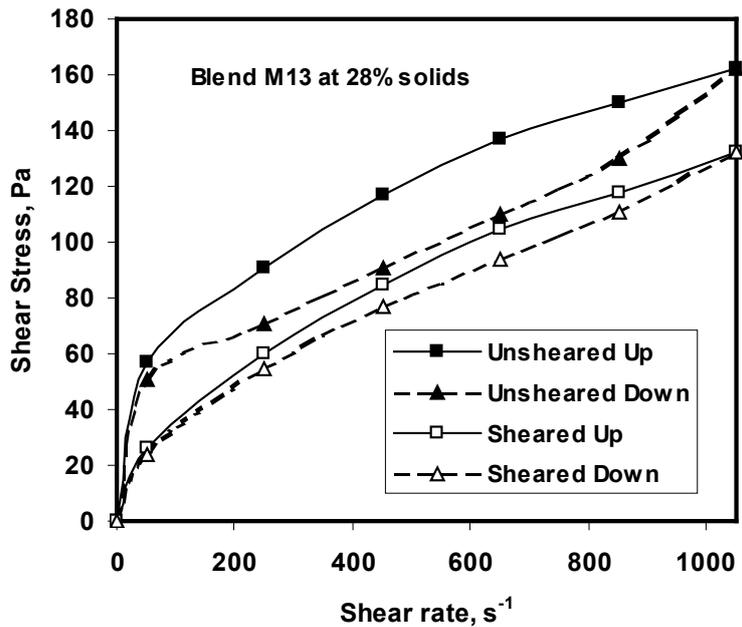


Figure 4 Examples of Real Flowcurves – Typical Laterite Slurry

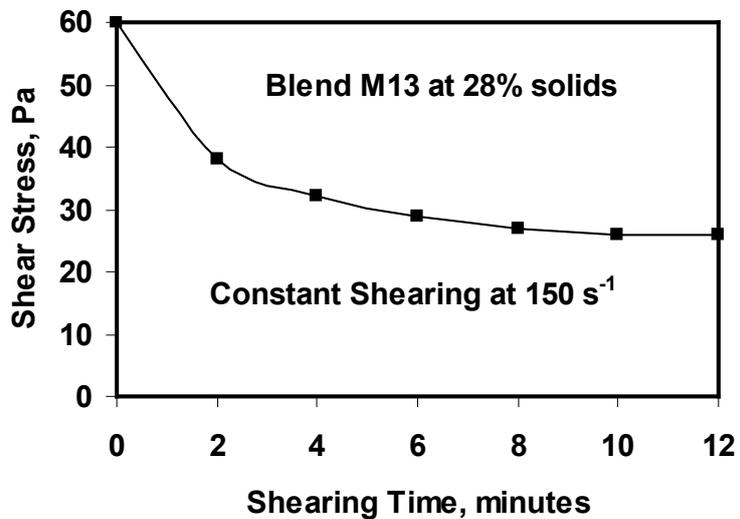


Figure 5 Example of Limited Time Dependency - Thixotropy

rheological models, Bingham Plastic and Ostwald de Waele could be applied with reasonable accuracy, based on the best-fit modeling. Pressure loss calculations [1] were carried out based on generally accepted criteria [18, 19]. The results covered the entire shear rate range tested and returned fairly similar friction loss values, except for the zero velocity fluid (Figure 7). The zero velocity exception was given by the power law-based Ostwald de Waele model, according to which, the pressure loss would be zero. The physical significance

of this fact is that the fluid would be free flowing, i.e. no pump start-up power would be needed. As can be seen in Figure 6, this would be in contradiction to reality. The example illustrates the importance of understanding the system to which the rheological model is being applied, rather than examining the mathematical predictions of the model in isolation.

It is also worth noting that (Figure 7) that the concentric cylinder rotational viscometry (CCRV) data accurately models the results obtained from a pump-loop. Therefore, pump loop testing is needed only for applications where the CCRV technique is not applicable, such as in the case of fast settling slurries containing coarse and/or high specific gravity solids. This is a significant result, since pump-loop testing is usually very costly compared to CCRV testing, and requires much larger quantities of sample.

FLOW BEHAVIOR OF LATERITE ORE SLURRIES

There is extensive literature describing the rheological behavior of lateritic slurries, both in general terms, as well as with reference to specific cases, ore deposits, processes, applications, etc. [1, 13, 14, 15, 16]. The purpose of this section is to provide a succinct comparative description of the rheological behavior of various lateritic ores slurries. The data was produced through commercial testwork carried out on laterite slurries originating from several deposits around the world. The main rheological characteristics, found to be common to most laterite ore samples tested, can be summarized as follows:

- Lateritic ore slurries of practical importance for extractive metallurgy display non-Newtonian flow behavior, best described by the Bingham plastic rheological model;
- Certain lateritic ores form slurries that display poor flowability characteristics at solids densities as low as 29%, characterized by yield stress values of 30 Pa or more. These lateritic ore types referred to in this paper as type "M"; consist mainly of a variety known as "dry laterites" [20].
- There are also lateritic ores that form slurries that display excellent flowability at solids densities as high as 42%, characterized by yield stress values of 30 Pa or less. These lateritic ore types, referred to in this paper as type "I" consist mainly of a variety known as "wet laterites" [20].
- The relative effects of temperature, dilution and dispersants on the flowability of type "M" lateritic ores are more pronounced than on

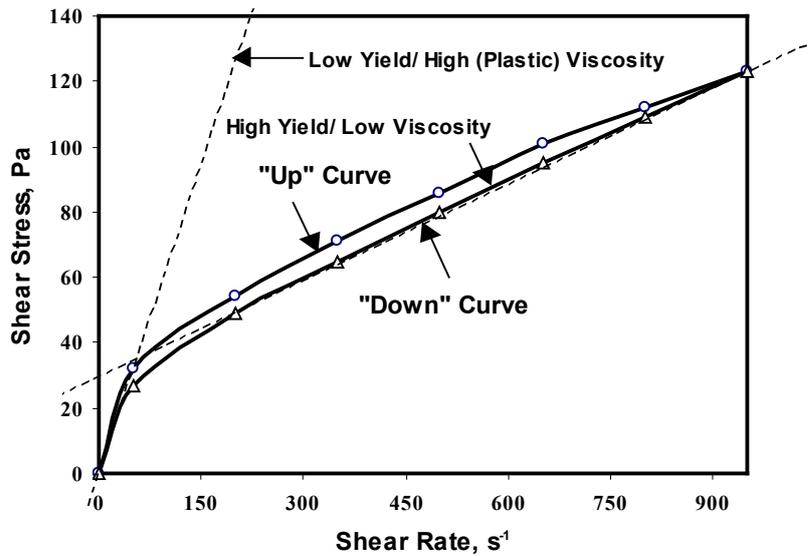


Figure 6 Assessing Rheology Data

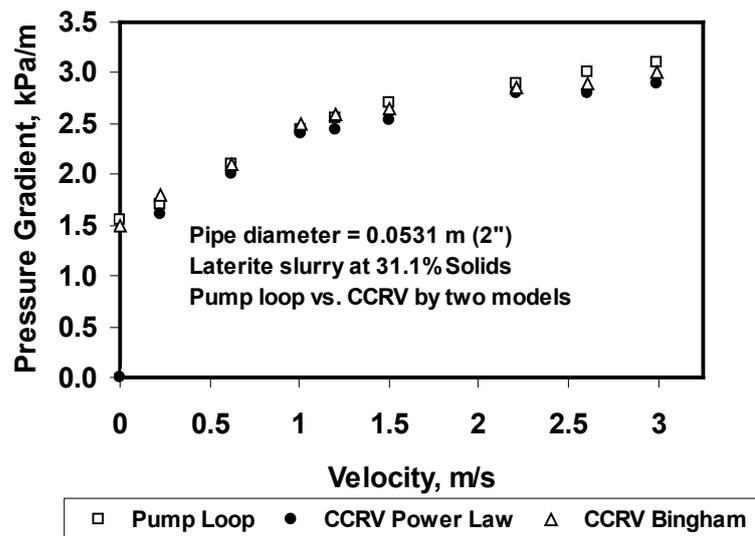


Figure 7 Comparative Pressure Calculations

type "I" ores. However, within the temperature range of 25 to 200°C, the overall flowability of the type "I" lateritic slurries is clearly superior to that displayed by type "M" slurries. That temperature range is relevant for the feeding and preheating stages of the high temperature autoclave acid leaching process.

- There are lateritic ores that form slurries with intermediate rheological properties between the two types defined above. The flowability of these slurries can be improved by ore blending, optimizing the salinity of the process water, controlled dilution during preheating and the use of rheological additives.

Comparative flowcurves of various lateritic slurries of type "M" and "I" are illustrated in Figure 8. The effect of temperature on the yield stress of these slurries is illustrated in Figure 9.

The underlying data illustrated in the graphical illustrations were selected to exemplify the two diametrically different flow characteristics, defined as such for the purpose of this work. Accordingly, laterites type "M" display the most difficult rheology whereas laterites type "I" display excellent flowability.

A general characteristic of type "M" laterite slurries is that they display high

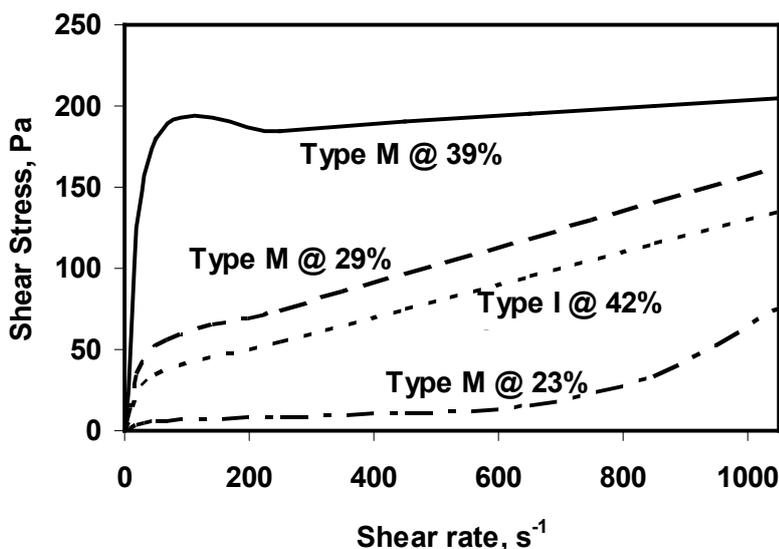


Figure 8 Comparative Flowcurves – Slurries Type “M” and “I”

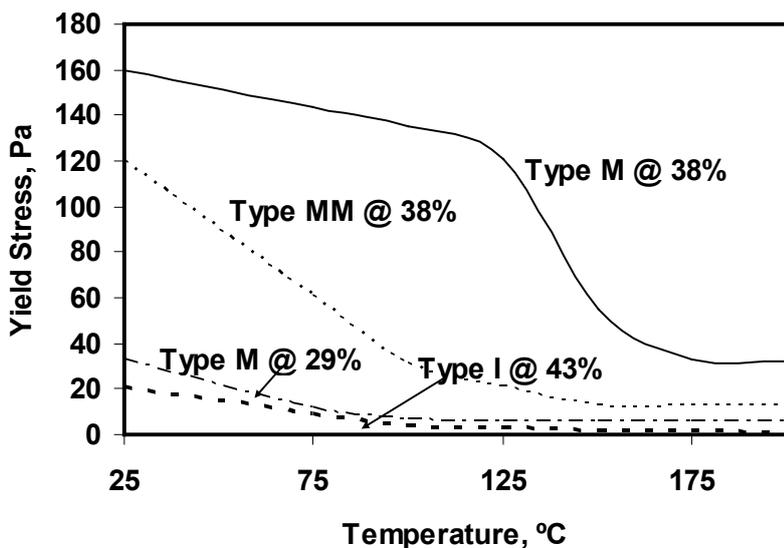


Figure 9 Effect of Temperature on Yield Stress – Slurries Type “M” and “I”

yield stress even at relatively low solids densities, such as the case with the 29% slurry displaying a yield stress of about 48 Pa. At higher solids densities, the “plug-flow” phenomenon is generally present. Type “M” lateritic slurries display a thixotropic tendency which allows them to dramatically increase the flowability; (even under these conditions, their flowability remains far below the flowability displayed by laterite slurries type “I”). Overall, type “M” slurries can generally be treated as time-independent, with well defined rheological properties.

A general characteristic for type “I” lateritic slurries is that they display low yield stress even at relatively high solids densities as illustrated by the case with the 42% slurry having a yield stress of about 26 Pa. The degree of thixotropic breakdown is less visible in these slurries, compared to type “M” slurries. In fact, diluted slurries may exhibit an anti-thixotropic behavior, limiting the allowable rate of shearing during metallurgical processing. The high temperature behavior of laterite slurries is very important during the heat exchange and subsequent autoclaving unit operations. While type “I” slurries

continue to display the most desirable behavior, the increase in their flowability on heating is not as dramatic as in the case of type “M” slurries. On the other hand, type “M” slurries generally need significant dilution (i.e. “M” at 29% solids) and in certain cases chemical modification (MM at 38% solids) to improve their flowability.

FLOW BEHAVIOR OF PROCESS SLURRIES

Typical slurry streams produced during the metallurgical processing of lateritic ores include the autoclave discharge (ACD), counter-current decantation underflow (CCD) and various precipitate samples (NTR). As noted above, these slurries tend to be chemically active, rendering their characterization time-dependent in a chemically-kinetic sense. From a purely rheological point of view, these slurries do not, however, present special flowability problems. The rheological properties of these slurries tend to be independent of the properties of the originating lateritic ore slurries.

Maximum yield stress values displayed by typical CCD slurries, measured at a discharge temperature of about 75°C ranged from 30 to 38 Pa, at slurry solid densities ranging from 45 to 49% by weight. The predominant rheological time-dependency consisted of thixotropic breakdown at the higher range of solids densities, in the thickener underflow discharge. Moderate rheopexy was observed in the case of more diluted slurries such as thickener feed. Maximum yield stress values displayed by typical NTR slurries, measured at a discharge temperature of about 65°C, ranged from 1 to 6 Pa, at slurry solid densities ranging from 36 to 40% by weight. The predominant rheological time-dependency consisted of rheopexy. The extent of rheopexic build-up was found to be directly proportional to the rate of shearing and inversely proportional to the solids density. The Bingham model could not be always applied for the NTR slurries, as a power law (Ostwald de Waele) type of behavior tended to prevail at higher shear rates. More complex models such as Hershley - Bulkley and Casson seemed to better reflect the rheological behavior of these slurries.

The ACD slurries displayed a fast settling behavior, rendering them unsuitable for CCRV measurements. A Metzner – Otto based testwork protocol was employed instead, allowing for the generation of baseline mixing torque data (Figure 10). The resulting power–torque curves allowed for the estimation of the power required to maintain the slurry in suspension and provide blending under a prevalent laminar regime. In addition, the approximate value of the equivalent Newtonian viscosity (mPa.s) of the slurry sample could be obtained, by comparing the torque responses to those generated by calibrated standard fluids. Flowcurves could also be produced within a relatively narrow range of shear rates, corresponding to the true laminar mixing regime.

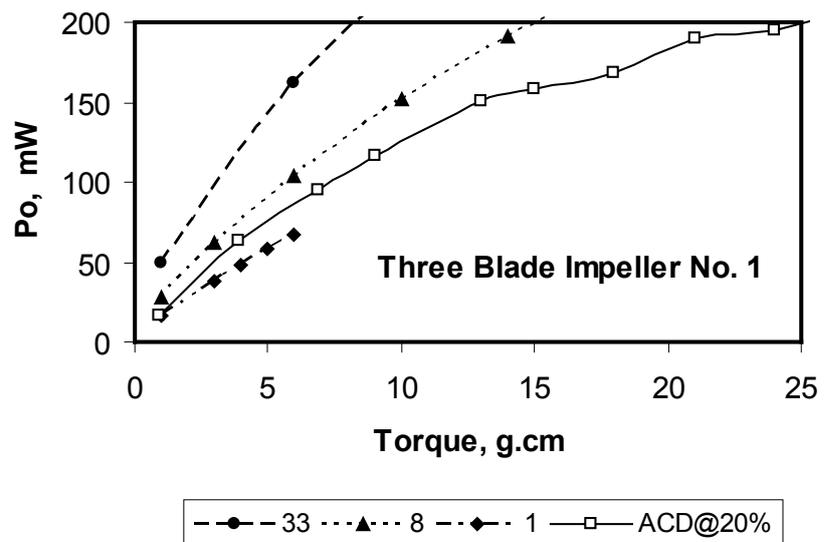


Figure 10 Example of Power – Torque Relationship and Comparison – ACD Slurry versus Calibrated Fluids (mPa.s)

FUTURE TRENDS

A wide applicability range for the test data generated, low cost and fast turn-around characterize rheological testwork. Most importantly, the rheology data have both predictive and application value, making rheology an efficient testing tool. Future trends include:

- Generation of base line rheology data during the initial stages of a testwork program. These data can be used for the estimation of optimum parameter ranges or even for preliminary scale-up and prefeasibility studies, involving capital and operating cost estimates. Thus, the necessity (or not) of a pilot plant campaign can be determined with reduced cost.
- Altering the rheology of laterite slurries to enhance their flowability is a challenge facing the exploitation of type “M” laterite deposits, characterized by problematic rheological behavior.
- There is a need for testing rheological behaviour at high temperatures owing to the lack of relevant physical data for most feed and process slurries encountered in laterite autoclaving processes.
- Process control using online rheology – The main driving force is the optimization of energy utilization in plant unit operations such as slurry transport, comminution, heat exchange and others.
- Establishing the optimum flowing

conditions creates the possibility of reducing the size of integrated pilot plants, with potential reductions in metallurgical testwork duration and cost.

- The renewed interest in hydrometallurgical processing of sulfidic nickel bearing ores will create the need for rheological data. Gas transfer in slurry systems is rheology-dependent. The rheology of these systems is greatly influenced by the size and particle size distribution, such as in the case of low-temperature oxidative processes. In addition to the size-fraction effect, the presence of molten sulfur in these systems could render them rheologically complex.
- The need for increasingly pure process intermediates and final products could lead in some cases to a requirement for the production of precipitates with sub-micron particle sizing. Apart from the fact that the chemical properties of such materials may be different from those of conventionally precipitated products, their rheological behavior is not predictable. The main question is whether or not a relatively monodisperse, nano-particulate fluid would follow the trend of increasing resistance to flow in proportion to the fineness of the solid particles. Furthermore, if the flowability behavior changes at some particular fineness, it would be necessary to quantify this change and determine when it takes place. Therefore, the rheology of nano-

particle slurries could be an important field of study in the future.

CONCLUSIONS

- Applied rheology testwork is needed because flowing properties influence the economics of continuous operations involving process slurries.
- Unambiguous test results can be achieved through accurate sample description and detailed rheological characterization, carried out in accordance with the theory of particulate fluids.
- The actual specific gravity of the solids contained in laterite slurries and various derived process slurry samples has been found to be dependent on the solids content of the respective slurries and related to their Bingham yield stress.
- Lateritic ore slurries are particulate fluids that display a non-Newtonian flow behavior best described by the Bingham plastic rheological model. Type “M” lateritic ore slurries typically display poor rheological characteristics and may not flow readily at solids densities as low as 29%, characterized by yield stress values of 30 Pa or more. Type “I” lateritic ore slurries typically display excellent flowability at solids densities as high as 42%, characterized by yield stress values of 30 Pa or less.
- The relative effect of temperature, dilution and dispersants on the flowability of type “M” lateritic slurries

is more dramatic than on type "I" slurries. However, the overall flowability of the type "I" slurries is clearly superior to the flowability displayed by type "M" slurries within the temperature range of 25 to 200°C.

- Certain lateritic ores form slurries that display rheological properties intermediate between types "M" and "I". The flowability of these slurries can be improved by ore-blending, optimizing the salinity of the process water, controlled dilution during preheating, and use of rheological additives.
- Some of the future trends in applied rheological testing include wider application of process rheology, use of rheological data to optimize the size and scope of process pilot plants, and development of process control applications based on rheological monitoring. Rheology data should find increasing importance in project due diligence studies. Rheological testing techniques will probably be driven towards examining higher temperature systems, systems containing finer (nano) particles, and three-phase systems with gases, solids and liquids that can result, for example, during the oxidative processing of sulfidic ores. Rheological data will also be used to alter and optimize the flowability of process slurries.

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