Significance of rheology characterisation in mineral flotation process performance

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Abstract. Mineral and metal extractive industries play an important role in the current global economics, and mineral processing is one of the key areas to achieve and maintain sustainability. It is known that the rheological behaviour of mineral slurries affects their processing. However, in addition to controlling the transportation of slurries around processing circuits, rheological behaviour also influences separation processes such as flotation. Although the impact of rheology in unit operations such as grinding and slurry transport has received considerable attention, this has not been the case for flotation. This paper explains the relationship between rheology and froth flotation performance. The results revealed that the mineral flotation performance can be improved by controlling the rheology in flotation process.

1. Introduction
Froth flotation is a process for selectively separating hydrophobic materials from hydrophilic gangues. This process is widely used in mineral processing, paper recycling, de-inking recycled newsprint, and waste-water treatment industries. Historically, flotation was first used in the mining industry as a great enabling technology of the 20\textsuperscript{th} century. Flotation process is schematically illustrated in Figure 1. The particles with attached air bubbles are carried to the surface and removed, while the particles that remain completely wet remain in the liquid phase. Froth flotation can be adapted to a broad range of mineral systems to selectively separate valuable mineral. For example, flotation is used in separating sulfide minerals from silica gangue, potassium chloride from sodium chloride, coal from ash, phosphate minerals from silicates.
2. Rheology in Froth Flotation

2.1 Rheology in Pulp Phase

The rheological behaviour of mineral slurries indicates the level of inter-particle interaction or aggregation, and therefore, it can be used as a useful processing control parameter. The flotation separation of minerals may be influenced by inter-particular interactions, and rheological data can offer a direct approach to further understand these interactions. For example, rheology has been used to investigate particle interactions in oxide minerals slurries [1, 2], clays [3, 4], coal [5], and sulfide minerals [6]. It should be noted that although the impact of rheology in unit operations such as grinding and slurry transport has received attention in the past, this has not been the case for flotation. In fact, the pathways by which the pulp or froth rheology influences flotation performance is not yet fully understood [7].

It is worth mentioning that accurately measuring the rheological properties of mineral slurries is difficult, since the solid particles tend to settle during measurement. Researchers have used methods such as pumping slurry during measurement [8], using capillary viscometers [9] or stirring the suspension while measuring with Couette-type viscometer [10], to overcome this problem. However, finding a proper practical way to measure the rheology of such slurries remains a challenge for research in this area. Turbulence is also another parameter which may affect the rheology measurements and therefore turbulence correction procedures have been suggested to process the measured data [11].

The significance of rheology in minerals processing has been reviewed previously [12, 13]. A direct measurement technique (Vane method) at a constant low shear rate mode, was applied to measure the yield stress of concentrated fine particles [14]. However, due to the practical limitations, it is often difficult to conduct measurements at such a low shear rate. In such cases, the yield stress can be estimated using mathematical models involving the extrapolation of the data to a zero shear rate. It is also worth mentioning that Nguyen and Boger have concluded that the Vane technique is the most suitable method for a material having yield stress of greater than approximately 10 Pa [15].

As mentioned, rheological investigations can be used to understand the interactions occurring in the flotation process [16, 17]. The viscosity of flotation medium may also affect the flotation recovery. A higher recovery of coarse composite copper bearing particles was reported by increasing the viscosity of the flotation medium (when a glycerol water mixture was used) [18].

The relationship between change in rheology (viscosity or yield stress), and flotation performance is shown in Figures 2 to 4 [6, 17, 19]. In Figure 2, the concentration of phyllosilicates or fibres has direct
relationship with the slurry yield stress, but it does increase the copper recovery in flotation. In Figure 3, the viscosity of the Carlin ore slurry was changed by adding dispersant. At the same time, the gold flotation recovery was considerably improved by about 5%. The data presented in Figure 4 were obtained by mixing montmorillinite and copper ore. It shows that the best copper flotation recovery is indeed obtained when the ore slurry has the lowest yield stress. For detail, please see the original paper published by Farrokhpay et al.[20].

Figure 2. Relationship between rheology and copper recovery in the presence of serpentine and nylon fibres

Figure 3. The effect of adding dispersant to gold flotation recovery and grade

Figure 4. The relationship between copper recovery and ore slurry yield stress (by adding clays)
2.2 Rheology in froth phase
As shown in Figure 1, flotation contains two phases of slurry (pulp), and froth. Froth has three phases of water, air, and solid. Therefore, it bursts and collapses if left for any length of time as water and solids drain from the bubble surfaces. Therefore, it was not possible to accurately measure the froth rheology until Li et al. introduced a reliable method to do that [21].

Rheology has been mentioned as an important froth property. In flotation plants, experienced operators use their fingers to test if the froth is viscous to adjust the operating variables [22]. Until recently, a very limited number of studies were available on froth rheology [23, 24]. These studies were performed in either batch flotation cells or in industrial cells using complex ore mixtures. The results showed that rheological measurements are strongly correlated with certain froth properties, such as solid or water content and froth grade. However, due to the complexity of the applied system, they were not able to identify the mechanisms that govern the rheological behaviour of froth. A correlation between froth rheology and the grade of hydrophobic and hydrophilic minerals (chalcopyrite and quartz, respectively) is shown in Figure 5 [22]. Shi and Zheng [22] used froth ‘torque’ as a proxy for shear stress. The torque values can be converted to shear stress values using equation provided by Nguyen and Boger [25]. A correlation has also been observed between froth viscosity and mineral recovery (and grade) in phosphate flotation [26]. However, the reason for the froth rheology change was not yet clear [27]. A more viscous pulp may result in a more stable froth [28]. Li et al. has exclusively investigated the froth rheology and its effect on flotation performance in recent years [21, 29-31]. They have observed correlation between froth viscosity and mineral recovery in froth flotation process.

![Figure 5](image.png)

Figure 5. Froth rheology as a function of froth flotation concentrate grade for (left) chalcopyrite and (right) quartz [22]

3. Conclusion
The relationship between rheology measurements, and froth flotation performance was discussed. It was shown that the mineral flotation recovery and/or grade can be improved by controlling the rheology in flotation process. Flotation consists of two separate phases of pulp (slurry) and froth, and it has been revealed that rheology of both phases is related to the overall flotation performance. However, it should be emphasized that one should choose the measurement method carefully. The particles in the pulp phase intend to settle (due to gravity), so rheology measurements should be done in a way to overcome this problem. Froth is also a three phase system (air, water and solid). Therefore, it bursts and collapses if left for any length of time during the rheology measurements. Reliable methods to measure the rheology of both phases are now available. Therefore, it is suggested to use the rheological measurements as a controlling tool in flotation process development.

4. References
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