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Effect of flotation froth properties on froth rheology

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ABSTRACT

Froth flotation is a widely used process of particle separation exploiting differences in surface properties. The froth performance in a flotation cell is expected to be affected by the froth rheology, as it affects the froth residence time that determines the probability of recovery of valuable minerals in the froth phase. Flotation froths have a similar structure to the gas–liquid foams whose rheology has been widely studied. However, to date, very little work has been done in the rheology of flotation froths owing to their instability and the presence of solid particles (on bubble surfaces and in the plateau borders) that are believed to influence froth rheology and complicate any investigation. In this paper, the effects of froth properties on froth rheology were studied by examining the results of 33 flotation tests performed under various conditions that resulted in changes in the froth properties and, consequently, the froth rheology. The experiments were performed in a 20 L continuous flotation cell. It was found that the bubble size and the fraction of lamellae covered by solids defined the froth rheology, while the presence of particles in the plateau borders contributed very little to the froth rheology. A model structure was developed by taking into account froth properties to predict froth viscosity.

1. Introduction

In flotation, the froth phase plays the role of transporting the hydrophobic minerals from the collection zone to the concentrate launder. Froth transportation consists of both vertical and horizontal motion: the vertical motion is defined by the flow of bubbles that carry particles moving from the pulp–froth interface to the launder lip level, while the horizontal motion describes the motion towards the overflow weir [1]. Drainage of valuable minerals occurs during froth transportation owing to bubble bursting and bubble coalescence. Froth residence time, which determines the probability of recovery of valuable minerals, is a function of the time bubbles take to move both vertically and horizontally. The vertical motion is driven by the superficial gas velocity. The horizontal flow is a consequence of three factors that include the force of gravity, the froth stability and the resistance to froth flow. The influence of the froth stability on the efficiency of froths in recovering valuable minerals has been extensively studied [2–5]. The resistance to froth flow is supposed to be directly associated with froth rheology, and, therefore, the importance of froth rheology on flotation performance has also been recognised. Shi and Zheng [6] and Farrokhpay [7] have clearly shown that froth rheology can affect the froth mobility as well as the froth stability, and ultimately influence the flotation performance. However, to date, it is not clear what froth properties affect froth rheology.

Rheology is a measure of the flow characteristics of a substance. It is usually represented by a rheogram which plots the shear stress of a fluid when subject to different shear rates. In general, a substance can either exhibit Newtonian or non-Newtonian behaviour, with the latter including dilatant, plastic, pseudo-plastic and Bingham behaviours [8,9]. Various types of rheograms are illustrated in Fig. 1. Viscosity as a key rheological term is a measure of the resistance of a material to deformation. It is a constant in Newtonian flow but shear rate dependent in non-Newtonian flow.

In order to fully understand what froth properties determine the froth rheology, it is firstly necessary to gain insight into the froth characteristics. From the study of aqueous foams, when the gas volume fraction is less than 0.73, bubbles disperse in the liquid phase without becoming attached to one another; at a gas volume fraction greater than 0.73, the bubbles start to pack and are separated by thin-plane-parallel films forming polyhedral cells (lamellae) [10]. The thin lamellae meet in lines (plateau borders) and the lines meet at vertices [11,12]. Flotation froth has a similar structure to dry foam. The air volume fraction in flotation froth usually exceeds 0.90 especially in deep froth due to rapid drainage. Furthermore, flotation froth is a gas–liquid–solid regime; there are solid particles present in the froth phase. Hydrophobic particles are mainly attached to the lamellae while both hydrophilic and hydrophobic particles (detached owing to bubble coalescence and bubble bursting) are present in the plateau borders and vertices. A typical froth structure with particles is shown in Fig. 2.

Flotation froths have a similar structure to foams, making it possible to begin the study of froth rheology by considering the rheology of foams (i.e. leaving aside the presence of solid particles). Practically, foam rheology is associated with bubble size and foam quality (the volume fraction of air in the foam) [13–16]. When foam is dry, its rheology is dominated by the bubble size [15,17]. However, a flotation froth

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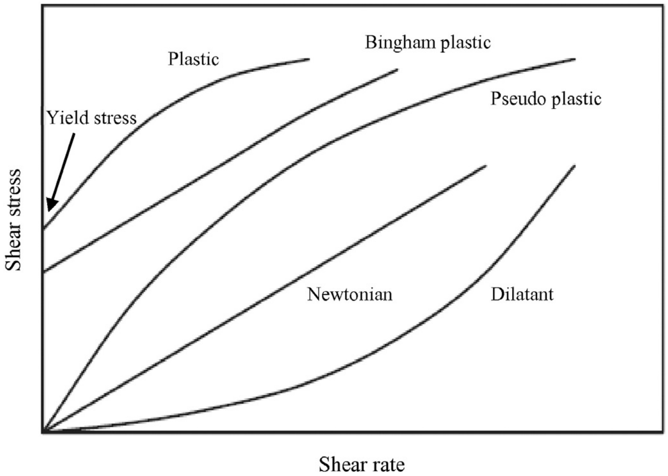

Fig. 1. Schematic diagram of shear rate as a function of shear stress for different types of fluid. After Mewis and Wagner [8].

differs from a two phase foam in that there are also solid particles present — both as attached particles on the lamella of the bubble surface and in the plateau borders which form between the bubbles. It is not yet clear how the presence of solid particles affects the rheology of flotation froths. The hydrophobic particles attached on the lamellae in flotation froth function as the surfactant adsorbed on the interface film in aqueous foam. The surfactant adsorbed on the interface film lowers the interface tension and resists bubble coalescence, stabilizing the foam. The presence of surfactant on the film is characterized as its adsorbing thickness [18]. In this study, the presence of solid particles attached to the lamellae can be represented by the fraction of lamellae covered by solid particles which takes into account the mass of solid particles attached to the lamella per unit area and the size distribution of the solid particles. It is expected that the particles on the lamellae change the bubble rigidity and smoothness. In addition, the particles trapped unselectively

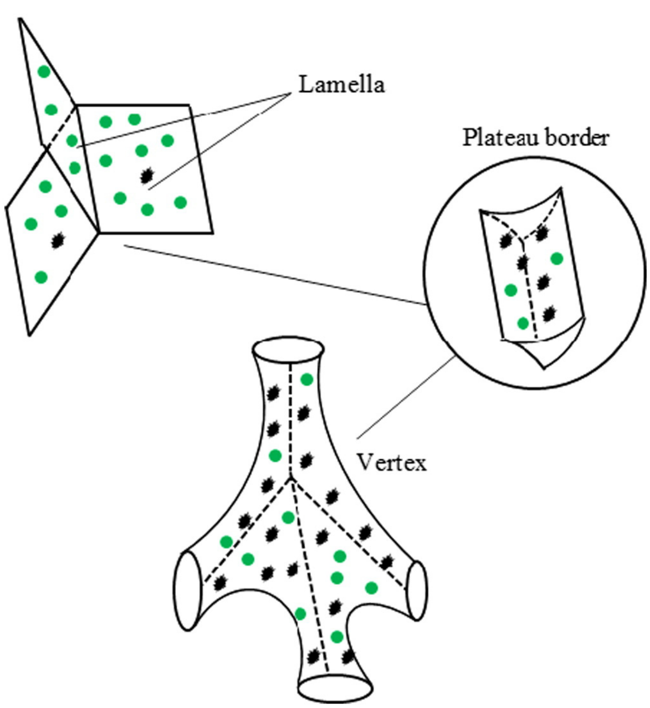

Fig. 2. Schematic of flotation froth (hydrophilic particle; hydrophobic particle). After Ventura-Medina and Cilliers [10].

in the plateau borders and vertices form the local solid–liquid suspension. According to the study of suspension rheology, the solids volume fraction in the suspension influences the rheology [19]. Hence, whether the solids volume fraction in the plateau borders and vertices is also a crucial factor affecting froth rheology needs to be investigated.

Previously, the authors have investigated the effects of various flotation conditions (viz. froth height, gas rate, impeller speed, feed particle size and feed grade) on froth rheology. A Central Composite Rotatable Design (CCRD) study was carried out, in which 33 flotation tests were performed in a 20 L continuously-operated flotation cell [20]. The froth rheology was measured using a method developed recently by the authors [21]. Ultimately, the flotation conditions influence the froth rheology through their effect on the froth properties. In this current work, the results of the previous experiments (from the CCRD study) are examined to fundamentally investigate the direct effect of the froth properties on froth rheology. The froth properties of interest were identified above as bubble size, fraction of lamellae covered by solids and the solids volume fraction in the plateau borders and vertices. The method of evaluating these froth properties is developed below.

2. Experimental

2.1. Flotation tests

The 33 flotation tests were performed in a bottom driven 20 L flotation cell with cross sectional dimensions of 30 by 30 cm. Table 1 shows the details of the 33 tests in which there are seven repeat tests (i.e. Tests 1, 9, 10, 12, 18, 19, and 26). The aim of this work is to create flotation froths with different froth properties and evaluate the effects of these froth properties on the froth rheology.

The flotation feed was a mixture of pure chalcopyrite and silica. The chalcopyrite was purchased from Geo Discoveries as bulk rock. The

Table 1
The conditions in the CCRD flotation tests [19].

Test	Froth height (cm)	Superficial gas velocity (cm/s)	Impeller speed (rpm)	Chalcopyrite particle size P80 (μm)	Copper grade (%)
1	7	1.4	900	80	1.0
2	6	1.0	750	50	1.4
3	6	1.8	1050	50	1.4
4	8	1.8	750	50	1.4
5	6	1.0	750	110	0.6
6	6	1.8	750	50	0.6
7	6	1.0	1050	50	0.6
8	6	1.8	1050	110	0.6
9	7	1.4	900	80	1.0
10	7	1.4	900	80	1.0
11	8	1.8	750	110	0.6
12	7	1.4	900	80	1.0
13	8	1.0	1050	110	0.6
14	8	1.8	1050	110	1.4
15	8	1.0	750	110	1.4
16	6	1.8	750	110	1.4
17	8	1.8	1050	50	0.6
18	7	1.4	900	80	1.0
19	7	1.4	900	80	1.0
20	8	1.0	750	50	0.6
21	8	1.0	1050	50	1.4
22	6	1.0	1050	110	1.4
23	7	1.4	900	140	1.0
24	5	1.4	900	80	1.0
25	7	0.6	900	80	1.0
26	7	1.4	900	80	1.0
27	7	1.4	1200	80	1.0
28	7	1.4	900	80	1.8
29	7	1.4	600	80	1.0
30	7	2.2	900	80	1.0
31	9	1.4	900	80	1.0
32	7	1.4	900	80	0.2
33	7	1.4	900	20	1.0