Slime coatings in froth flotation: A review

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ABSTRACT

Slime coating is a significant phenomenon in froth flotation. The adverse effects of slime coating, by which a value mineral is covered by slimes and prevented from direct contact with collectors and/or air bubbles, have been recognized for decades. It happens ubiquitously in the flotation of various minerals, including sulfide minerals (sphalerite, galena, chalcopyrite, pentlandite, etc.), oxide minerals (hematite, wolframite, scheelite, etc.), salt minerals (fluorite, potash, etc.), coal and bitumen. In this paper, an attempt was made to present a comprehensive review of slime coatings in froth flotation including particle adhesion mechanisms, slime coating measurement techniques, influencing factors, control methods and mitigation measures. It was shown that the classical Derjaguin–Landau–Verwey–Overbeek (DLVO) theory, and the extended DLVO theory, are the mainstream mechanisms underpinning slime coatings. According to their sources, the slimes can originate from gangue minerals and value-gangue composite particles, or from colloidal compounds formed during ore dressing due to grinding, mineral surface oxidation and chemical precipitation. The origin and property of the slimes, the types and concentrations of electrolytes, and solution pH are the main factors influencing slime coatings. Current techniques employed to study slime coatings are mainly focused on the interactions between two particles in a static and ideal environment, which cannot account for slime coatings under commercial froth flotation conditions. Physical mitigation methods such as ultrasonic treatment and high intensity conditioning are often more effective than chemical mitigation methods that usually entail the use of dispersants. Gaps in the existing literature are discussed and potential research directions are suggested.

1. Introduction

With decreasing grade and increasing complexity of mineral dissemination, ores have to be ground to very fine sizes to liberate value minerals for recovery. In the process, large quantities of fine gangue minerals are generated due to either the fine grind or the clayey nature of the ore (Kusuma et al., 2014; Liu and Peng, 2014; Wang et al., 2015a). These fine gangue mineral particles are collectively called "slimes", and they exert many detrimental effects on froth flotation, a mineral separation technique most widely used today. The slimes increase reagent consumption and pulp viscosity, and are liable to entrain into froth product (Arnold and Aplan, 1986a; Brown and Smith, 1954; Burdon et al., 1976; Forbes et al., 2014; Mishra, 1978; Wang et al., 2015b; Yu et al., 2015). The slimes can also coat the surfaces of value minerals and significantly change the flotation behavior of the latter. Intuitively, the slimes coated on value mineral surface form a hydrophilic "armor" preventing the value mineral from direct contact with collectors and/or air bubbles, lowering flotation recovery (Arnold and Aplan, 1986a, 1986b; Bandini et al., 2001; Forbes et al., 2014; Jorjani

et al., 2011; Jowett et al., 1956; Liu et al., 2002; Tabatabaei et al., 2014; Wang et al., 2015b; Yao et al., 2016a; Zhang and Peng, 2015).

A search of open literature shows that slime coatings are ubiquitous in the flotation of various minerals, including sulfide minerals (sphalerite, galena, chalcopyrite, pentlandite, etc.), oxide minerals (hematite, wolframite, scheelite, etc.), salt minerals (fluorite, potash, etc.), coal and bitumen. In most cases, the slimes are composed of kaolinite, montmorillonite, illite, serpentine, quartz, dolomite, and smithsonite. In the early days, researchers attributed slime coatings to electrostatic attraction because the slimes and value minerals carried opposite charges (Bankoff, 1943; Fuerstenau et al., 1958; Iwasaki et al., 1962; Sun, 1943). However, the ensuing research showed that slimes could coat the value mineral surface even when they carried the same sign of charges (Oats et al., 2010; Wang et al., 2013; Yao et al., 2016b; Yu et al., 2015). The classical Derjaguin–Landau–Verwey–Overbeek (DLVO) theory has been used to understand the slime coating phenomenon from a chemical standpoint (Chen et al., 1999a; Oats et al., 2010; Yao et al., 2016a; Yu et al., 2015), although some attributed slime coatings to grinding (Bandini et al., 2001; Holuszko et al., 2008). Much

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of the reported research on slime coatings was focused on identifying slime coatings, but few studies confirmed the existence of slime coatings unequivocally. Furthermore, the purpose of studying slime coatings is to control it, but so far, few effective ways have been reported and implemented to minimize the adverse effects caused by slime coating either in laboratory or in commercial flotation operations.

It is therefore imperative to understand and consequently to control slime coatings in froth flotation. In the following, the open literature on slime coatings in froth flotation is reviewed with an objective to provide a comprehensive overview of the slime coatings in froth flotation and to seek measures that can be taken to mitigate the slime coatings problem in mineral flotation.

2. Mechanisms of slime coatings

2.1. DLVO theory

The classical DLVO theory, which sums the universal van der Waals interaction with electrostatic interactions, has been widely used to explain the aggregation and dispersion of colloidal particles. In the minerals industry, researchers used DLVO theory to explain the interaction between mineral particles in water (Behrens et al., 2000; Celik and Bulut, 1996; Elimelech et al., 2013; Yoon and Mao, 1996). Oats et al. (2010) calculated the interaction forces between coal and clay particles using DLVO theory and reported that the calculation could account for the experimental observations in the coal and clay particles suspensions. Their results showed that the van der Waals attraction governed the clay coatings. Similarly, Chen et al. (1999a) proposed that van der Waals force was the dominant force of adhesion for gangue slimes attachment to coarse particles.

There are two methods to calculate the Hamaker constant for the van der Waals interaction of mineral 1 with mineral 2 across a water medium. One is the Hamaker approach (microscopic), and the other is the Lifshitz approach (macroscopic). The Hamaker approach is based on the assumption of molecular pairwise additivity and gives a good approximation for gases and often for media interacting across a vacuum or low-pressure gas, but it often fails to predict interactions across condensed phase media like water. In the latter case, the Lifshitz theory, which is based on quantum physics, is more applicable and it often predicts values of the Hamaker constant significantly higher than the Hamaker approach (Berg, 2010). DLVO energy curves between coal and clay particles calculated by the two methods are different and even contradictory (Oats et al., 2010; Zhang et al., 2009). For example, the total DLVO energy between coal and clay particles calculated by Zhang et al. (2009) and Yu et al. (2015) using the Hamaker approach was positive in the whole range of separation distance, so the coal and clay particles repelled each other, which could not explain the clay coatings on coal surface. However, the DLVO calculation based on Lifshitz approach by Oats et al. (2010) showed that the van der Waals attraction was strong enough to overcome the electrical double-layer repulsion, resulting in a net attraction between coal and clay particles at a close separation distance.

When calculating the electrostatic force between particles, zeta potentials obtained from experimental measurements are often used. However, clay particles have a plate-like structure with basal and edge surfaces that carry different charges (Gupta et al., 2010). The measured overall zeta potentials are misleading because they are not a true measure of either the basal face potential or the edge potential. In addition, it is recognized that the classical DLVO theory fails when the surfaces are very hydrophilic or very hydrophobic, necessitating consideration of additional interaction forces such as hydration and hydrophobic force (Derjaguin and Churaev, 1989). The summation of electrostatic interaction, van der Waals interaction and other interactions such as hydration and hydrophobic interactions results in the extended DLVO theory (EDLVO) (Lyklema, 2005), and it is often considered to better represent particle interactions. For instance, Yao et al.

(2016a, 2016b) reported that the interaction behaviors between magnesite, dolomite and quartz are better explained by the EDLVO theory than by the classical DLVO theory.

2.2. Deposition of colloidal compounds formed during grinding

Comminution of ores is almost always carried out before froth flotation. Researchers noticed that slime coatings may be a result of comminution (especially grinding), through the formation of a hydrophilic colloidal slime layer on the value mineral surface during comminution. For example, sphalerite can be heavily oxidized during dry grinding when the mill is open to air, forming smithsonite ($ZnCO_3$) slime coating on the surface of sphalerite, depressing the hydrophobicity of sphalerite (Holuszko et al., 2008). Steel grinding media are routinely used in flotation circuit, and the formation of colloidal iron oxide/hydroxides originating from the grinding media can form slime coatings on galena surface through van der Waals and electrostatic interactions governed by DLVO theory, exerting a significant detrimental effect on the flotation performance of galena (Bandini et al., 2001; Learmont and Iwasaki, 1984). The compounds formed during grinding are often reported as colloidal particles, and the colloidal particles may experience a stronger attraction to the mineral surface due to the compaction or impact caused by the grinding media. Fayed and Otten (2013) reported that plate-like agglomerates can be formed due to the compaction action caused by grinding media. From a practical perspective, more attention should be focused on slime coatings caused by deposition of colloidal compounds during grinding as it is a common step preceding flotation.

2.3. Chemical precipitation

Some researchers reported that slimes were bound to the mineral surfaces through a chemical reaction (Dorenfeld, 1953; Taggart et al., 1934). Ma et al. (2014) reported that calcium ions released by the hydrolysis of gypsum reacted with Na_2CO_3 to form calcium carbonate which coats the surface of a molybdenum-tungsten mineral, resulting in a lower flotation recovery (Ma et al., 2014). Through solution speciation modeling, Wang et al. (2013) proposed that precipitation of chrysotile, dolomite, hydroxyapatite and chrysotile may have occurred on the surface of coal particles. These are hydrophilic precipitates and likely have a negative effect on coal flotation (Wang et al., 2013). The type of the chemical precipitation is closely related to the solution chemistry of the pulp, and the conditions for precipitate formation and its coating mechanism need further research.

3. Slime coatings detection and quantification techniques

It is suggested that slime coatings can be detected by indirect macroscopic methods such as a reduction of flotation recovery, a change in particle settling rates, and a change in rheological properties of slurry. However, these methods may not give an accurate account of true slime coatings (Arnold and Aplan, 1986a; Xu et al., 2003; Zhang et al., 2016), as there can be more than one reason for the observed macroscopic behaviors. For example, clay minerals can affect froth flotation through slime coating but also through other ways, such as affecting froth stability, changing pulp rheology and covering bubble surfaces, that also lower flotation recovery of value mineral (Cruz and Peng, 2016; Farrokhpay and Bradshaw, 2012; Forbes et al., 2014; Ndlovu et al., 2015; Ndlovu et al., 2014). Thus, it can be misleading simply attributing a lowering in flotation recovery of value minerals to slime coatings. Similarly, the settling of value mineral particles may have a "mopping" effect that can trap clay particles even when heteroaggregation does not occur. In addition, the solid concentration and the particle network structure in a slurry can significantly affect its rheological properties and transform a Newtonian fluid to a non-Newtonian fluid even when aggregation does not occur (Cruz et al., 2013; Cruz