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# Variability of lead-zinc sulfide ore slurry rheological properties and its influence on flotation conditions

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**Abstract:** We investigated how the rheological characteristics of a flotation slurry change in response to variations in mineral species, slurry concentration, and particle size; slurry pH; and collector and rheological control reagent concentrations using slurries containing galena, sphalerite, quartz, and kaolinite. The results indicate that reducing particle size and increasing slurry concentration leads to varying degrees of increase in apparent viscosity and yield stress. At the same particle size, the slurry exhibits the following order of apparent viscosity and yield stress: kaolinite > galena > sphalerite > quartz. In addition, as the slurry's apparent viscosity and yield stress increase, the rheology decreases, creating progressively unfavorable conditions for the flotation of lead, zinc, and other valuable minerals. Furthermore, changes in pH have no significant effect on the slurry's rheology when the slurry is comprised of gangue mineral. Moreover, galena and sphalerite depict particle agglomeration in the slurry. Ultimately, the addition of sodium silicate as a rheological control reagent substantially enhances the slurry's rheological properties. This results in a system where problematic minerals like kaolinite are more effectively dispersed, thereby promoting efficient lead-zinc mineral flotation. Regarding the flotation of lead sulfide and zinc minerals, the addition of kaolinite raises the apparent viscosity of the mixed slurry, hindering the flotation of the valuable minerals. Conversely, quartz lowers the apparent viscosity aiding the flotation separation process. Understanding the relationship between flotation conditions and the pulp's rheological properties can provide valuable guidance for subsequent flotation tests.

***Keywords:*** lead-zinc sulfide ore, slurry rheology, apparent viscosity, yield stress, particle agglomeration

## 1. Introduction

Rheology is a distinct branch of physical mechanics that explores how objects deform and flow by examining factors like stress, strain, temperature, time, and viscosity. It investigates how fluids interact with particles and their microstructures, and how those interactions lead to changes in mechanical characteristics (Barnes et al., 1989; Verlag and Issn, 1979). Rheology is important to mineral processing research and application, serving as a vital parameter for process control across various stages—such as grinding, re-election, flotation, transportation, filtration, and separation (Boger, 2000; Farrokhpay et al., 2005). In this capacity, rheology provides a foundational basis for research into mineral processing activities (Becker et al., 2013).

Slurry rheology plays a crucial role in tailings transportation, grinding efficiency, chemical dispersion within the slurry during flotation operations, and filtration (Shi and Napier-Munn, 2002; He et al., 2004). The flotation process is influenced by the pulp's rheology, which arises from particle and bubble collisions. As the flotation pulp's apparent viscosity and yield stress increase, it creates greater resistance to particle and bubble movement. This reduces the likelihood of particles and bubbles colliding and adhering to each other. Consequently, the mineralization of bubbles becomes difficult, leading to decreased dispersion of mineralized bubbles in the pulp and a reduced uplift of mineral particles associated with these bubbles. This demonstrates the substantial impact of pulp rheology on the flotation process.

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Because a diverse set of variables interact with each other during the flotation process, rules governing changes in slurry rheological properties (e.g., apparent viscosity and yield stress) are very complex and necessitate comprehensive consideration of a variety of flotation conditions to obtain optimal slurry rheological properties (Wang and Li, 2020; Song et al., 2001). Specifically, the slurry's rheological properties are influenced by factors such as mineral species and particle size; slurry concentration (Zeng et al., 2023; Farrokhpay, 2012), temperature, strength (Zhao, 2007), and pH; and flotation chemicals, among others (Feng and Wen , 2017; Chen et al., 2010; Hintikka and Leppinen, 1995). Changes in these rheological properties directly impact the collision, adhesion, rise, and flotation of particles and bubbles. Thus, studying the relationship between flotation conditions and slurry rheological properties provides valuable guidance for optimizing the flotation process (Muster and Prestidge, 1995; Cruz et al., 2019).

Das et al. (Das et al., 2010) investigated the effect of montmorillonite, a clay mineral, on slurry rheological properties and the flotation process. Results showed that as the amount of montmorillonite in the slurry increased, it significantly changed the slurry's rheological properties, drastically raising the apparent viscosity and negatively impacting the flotation index. After incorporating montmorillonite with varying particle sizes, Mueller et al. (Mueller et al., 2009) found that smaller particle sizes result in more complex rheological properties, such as shear thickening and network structure aggregation, which inevitably complicates the separation process. Nestor Cruz et al. (Nestor et al., 2019) found that kaolin and bentonite, two other clay minerals, exhibit pseudoplastic characteristics, behaving as Newtonian fluids at low solids concentrations and non-Newtonian fluids at high solids concentrations. Furthermore, as the concentration of clay minerals in the slurry increased, the slurry's yield stress and apparent viscosity also increased.

Different deposits of lead-zinc sulfide ore veins significantly vary in their mineralogical components, which results in considerable variations in separation behavior and selection indexes (Gustafsson et al., 2000; Chen and Peng, 2008). Most beneficiation technologies for developing and utilizing lead-zinc sulfide ore resources employ the flotation process (Gupta et al., 2011; Wang et al., 2020). However, the flotation pulp, being a suspension system, is prone to settling and instability, making its rheological properties difficult to detect and complex to analyze (Montalti et al., 1991; Papo et al., 2002). Research has demonstrated that variations in gangue mineral components, particle size, and flotation chemicals (Cruz et al., 2015) affect the slurry's rheological properties, making them more complex (Zhang and Peng, 2015) and significantly increasing the slurry's viscosity. As such, there is a need to characterize the changes in rheological properties of the lead-zinc sulfide ores and their impact on flotation effectiveness.

This study focused on slurries comprised of the valuable minerals galena and sphalerite, as well as the gangue minerals quartz and kaolinite; and was conducted to determine the effect of mineral species, particle size, composition, pulp concentration, pulp pH value, collector concentration, and rheological control reagent concentration on the pulp's rheological properties. Additionally, agglomeration tests were conducted to explore the relationship between particle aggregation and dispersion and their impact on the slurries' rheological properties.

## 2. Methods

### 2.1. Materials

The galena, sphalerite, kaolinite, and quartz samples used in this study were obtained from Tieling, Liaoning Province; Chifeng, Inner Mongolia; Tangxian, Hebei; and Fuping, Hebei, respectively. X-ray diffraction analysis (Fig. 1) shows that the purity of all four samples is > 95%. Horizontal ball milling jars made of nylon and zirconia ceramic balls were used to grind the minerals. Subsequently, the milled products were dry-screened into the four grain sizes (a:150-74, b:74-38, c:38-23, and d:-23 μm) used throughout the experiments. Analytical grade sodium diethyldithiocarbamate served as the collector, while analytical grade hydrochloric acid and sodium hydroxide served as the pH rheological control reagents. Chemical grade butyl sodium xanthate and deionized water were also used in these experiments.

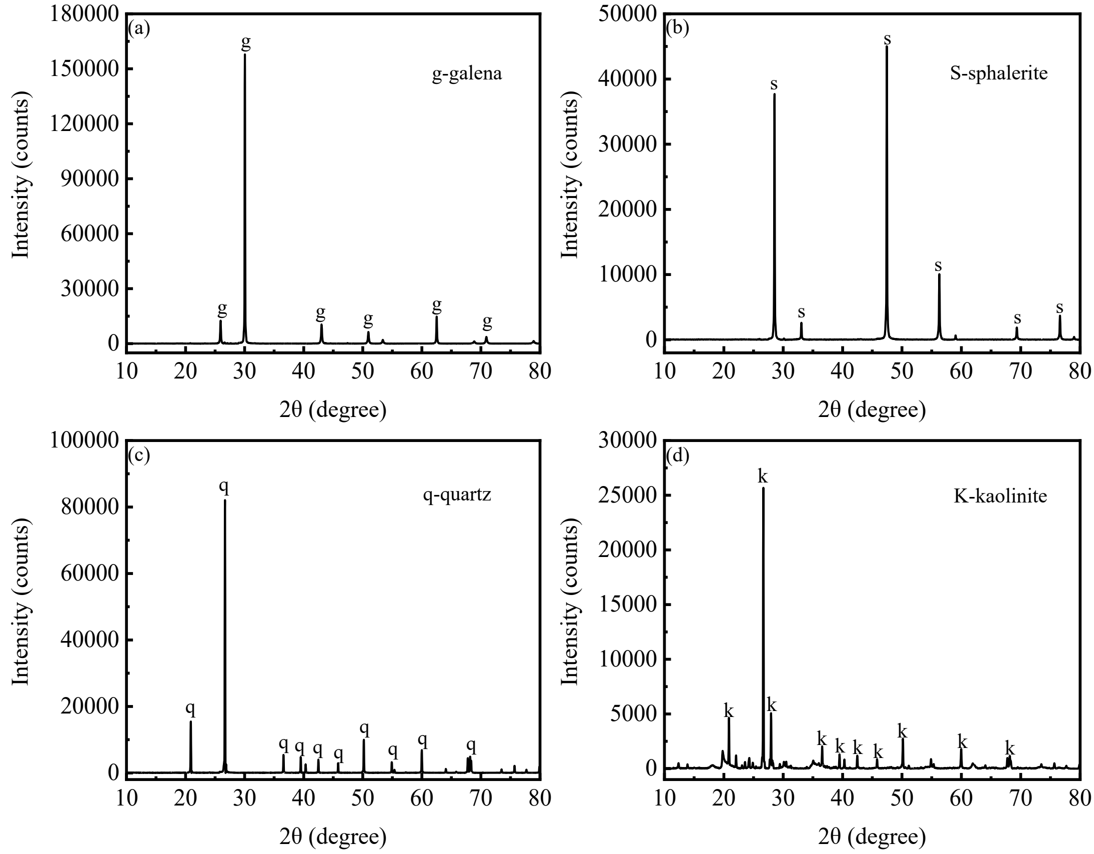


Fig. 1. XRD patterns of the (a) galena, (b) sphalerite, (c) quartz, and (d) kaolinite mineral samples used in this study

## 2.2. Detection and analysis of slurry rheological properties

The flotation slurry, a solid-liquid-air three-phase suspension system, is prone to settling and instability. Thus, the experiments were conducted using an Anton Paar MCR72 (in Fig. 2)rotational rheometer to minimize the impact of particle settling on the slurry's rheological properties. In addition, the traditional cylindrical mixing rotor was replaced with a paddle-type rotor to reduce the measurement error caused by particle settling. The paddle-type rotor, which was controlled by a motor, was immersed in the sample cup to stir the slurry and measure its rheological parameters.

The slurry samples were prepared by mixing the mineral powder with deionized water. First, the slurry was pre-sheared for one minute at a shear rate of 300 $s^{-1}$ to fully disperse the mineral particles. Stirring was then stopped for 15 s to stabilize the slurry and prevent rotational flow. During the measurements, the shear rate ranged from 20~300 $s^{-1}$. Each measurement lasted two minutes, and was repeated three times. For measurements at the same shear rate, the shear rate was set to 160 $s^{-1}$, and the procedure was repeated twice.

The rheometer test directly obtains parameters such as shear stress, shear rate, and apparent viscosity for each rheological measurement. Generally, the slurry's rheological properties are characterized by the relationship between the shear stress and shear rate. The slurry's yield stress was obtained using the Herschel Buckley model fitting.

## 2.3. Granular agglomeration test

The agglomeration test, which was carried out in 250 mL beakers, was conducted on fine-grained minerals under different agent concentrations. The minerals were prepared into a slurry with a mass concentration of 2.44 wt%, then subjected to ultrasonic dispersion for five minutes. Subsequently, various concentrations of collector and sodium silicate were added, and the pH was adjusted to 9.5-10.0 (11.5-12.0 for butyl xanthate). The slurry was stirred by a flotation machine for five minutes. A small amount of the slurry was then transferred to a slide, where the agglomerate morphology was observed under a polarized light microscope. The particle size distribution of the agglomerates was determined using a laser particle size analyzer.

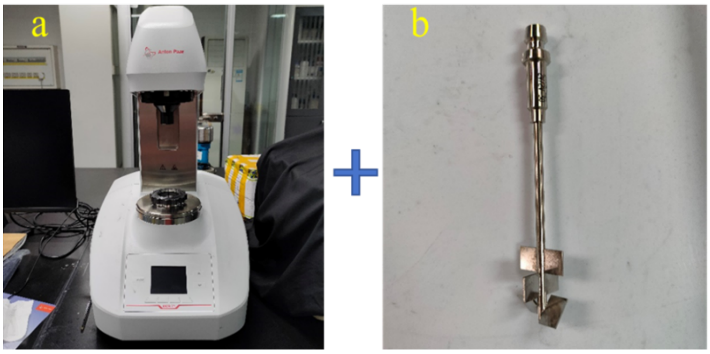


Fig. 2. Rheometer used in the experiment (a) rheometer;(b) paddle rotor

### 2.4. Flotation

The pure mineral test was conducted using an XFG type hanging tank flotation machine. Initially, pure mineral samples were mixed with deionized water to form a slurry and then added to the flotation tank. The flotation machine's rotational speed was set to 1800 r/min. After mixing the slurry for two minutes, the pH was adjusted using HCl or NaOH. The collector was added and the mixture was stirred for another two minutes. Aeration and bubble scraping were performed for two minutes to collect the flotation foam, which constituted the concentrate product. The remaining slurry in the flotation tank comprised the tailings product. After drying, weighing, and assaying the concentrate and tailings, the grade and recovery of the concentrate were calculated.

## 3. Results and discussion

### 3.1. Effects of mineral species, particle size, and pulp concentration on rheological properties

Figs. 3-6 demonstrate that at low slurry concentrations, the apparent viscosity and yield stress of the four mineral slurries are low. However, as the slurry concentration increases, the apparent viscosity and yield stress of the sphalerite, galena, and kaolinite slurries rise rapidly. Essentially, as the slurry concentration increases, the slurry transforms from a Newtonian fluid to a non-Newtonian fluid. Yield stress begins to appear and the apparent viscosity increases exponentially. Additionally, the apparent viscosity and yield stress of the slurry significantly increased as the particle size of sphalerite, galena, and kaolinite decreased. As shown in Fig. 3, when the slurry concentration is 28.57 wt%, the apparent viscosities of sphalerite slurry with particle sizes of -150+74 and -74+38 μm are 12.57 and 12.80 mPa·s, respectively; while the yield stresses are both below 0.036 Pa. In contrast, for the -23 μm sphalerite slurry at the same concentration, the apparent viscosity is 16.00mPa·s and the yield stress is 0.39Pa.

Galena (Fig. 4) and sphalerite (Fig. 3) exhibit similar changes. As the system's mineral particle size decreases and the proportion of fine-grained particles increases, particle collisions become more intense, internal friction rises, and the interaction between particles strengthens. This results in the formation of a more robust structure. With respect to flotation operations, as the particle size becomes finer and the content increases, the apparent viscosity of the pulp rises. This prevents the mineral particles from effectively dispersing, increasing their specific surface area. Consequently, more flotation chemicals are consumed and their selectivity decreases, leading to reduced mineral recovery and negatively impacting the concentrate grade.

As depicted in Fig. 5, the apparent viscosity and yield stress of quartz also increase with rising slurry concentration and finer particle size, although they remain generally low. For a quartz slurry with a concentration of 34.78 wt% and particle size of -23 μm, the apparent viscosity is 18.02 mPa·s and the yield stress is 0.08 Pa. Compared to the kaolinite, galena, and sphalerite slurries, this indicates that quartz particles exhibit a good state of dispersion.

For slurries containing mineral particles of identical size, kaolinite exhibited higher apparent viscosity and yield stress compared to quartz, which showed the lowest values for both properties. Chen et al. (Chen and Peng, 2018) similarly observed that clay minerals belonging to the kaolinite group tend to have higher apparent viscosity. Decreasing the particle size of the same mineral results in lower apparent viscosity and yield stress, while an increase in yield stress indicates a more complex structure within the slurry. To obtain deeper insights into the formation of particle agglomerates and the selective dispersion and agglomeration of minerals in fine-grained (-23 μm) flotation slurries, herein, the rheological characteristics of four different mineral particles were examined using this fine-grained particle size.

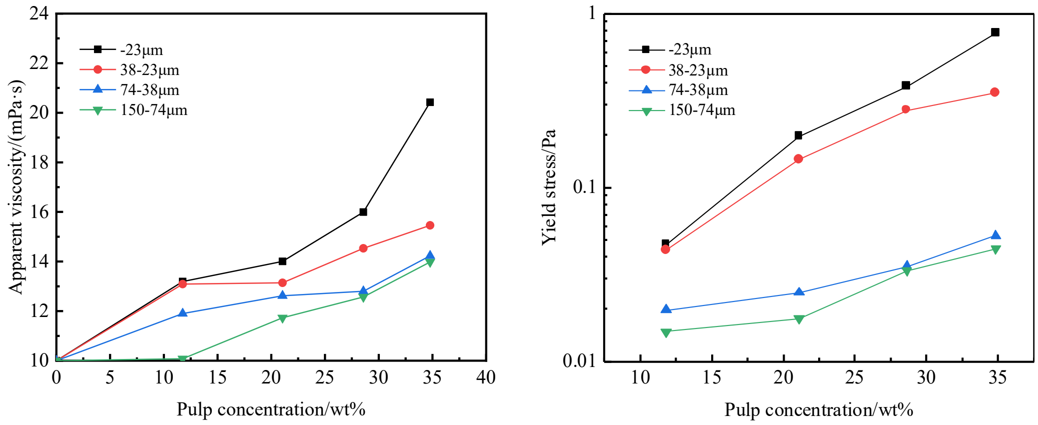


Fig. 3. Effect of slurry concentration on apparent viscosity (left) and yield stress (right) of sphalerite slurry with different particle sizes (pH 7.56)

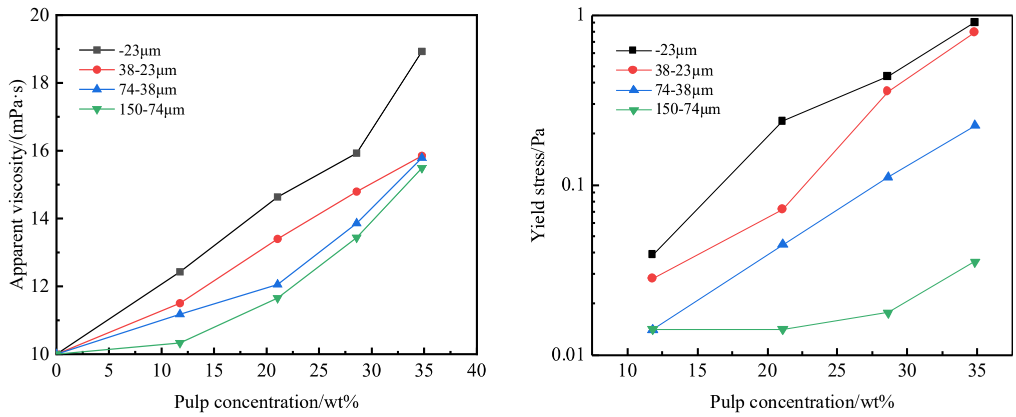


Fig. 4. Effect of slurry concentration on apparent viscosity (left) and yield stress (right) of galena slurry with different particle sizes (pH 6.42)

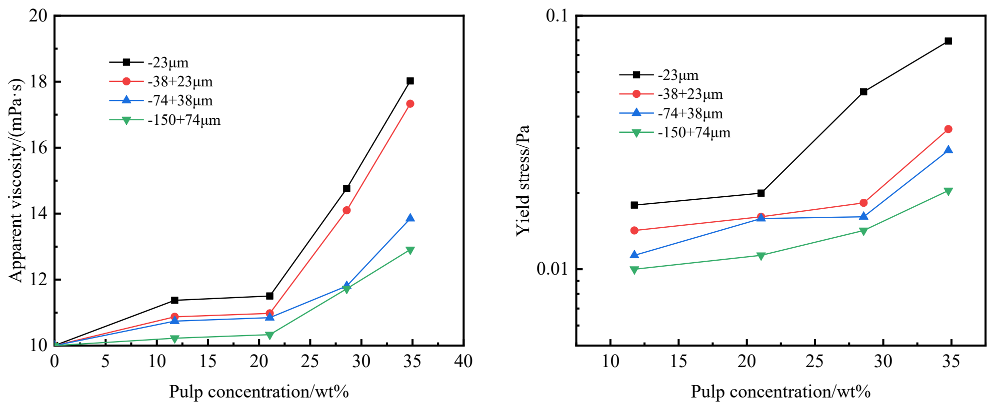


Fig. 5. Effect of slurry concentration on apparent viscosity (left) and yield stress (right) of quartz slurry with different particle sizes (pH 6.72)

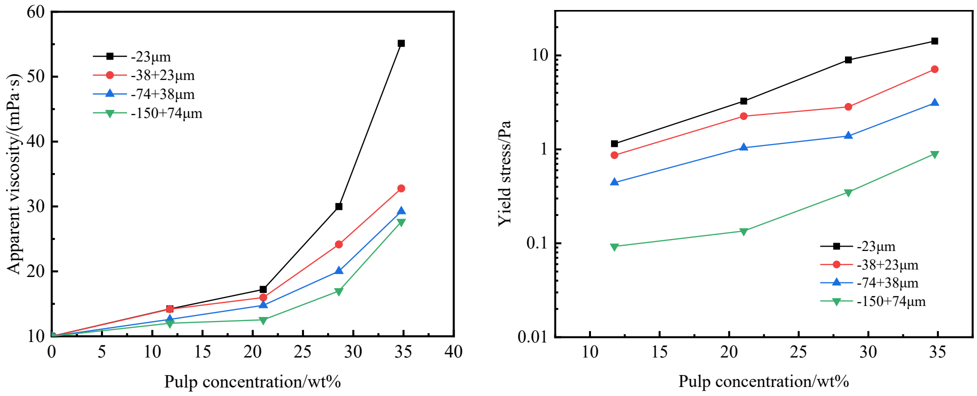


Fig. 6. Effect of slurry concentration on apparent viscosity (left) and yield stress (right) of kaolinite slurry with different particle sizes (pH 8.66)

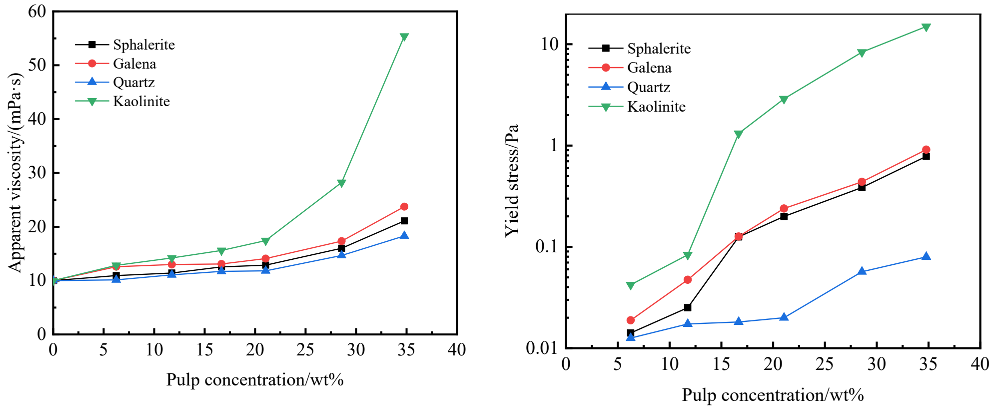


Fig. 7. Apparent viscosity (left) and yield stress (right) of fine-grained (-23 μm) mineral slurry as a function of slurry concentration (pH 9.5-10.0)

Fig. 7 depicts how the apparent viscosity and yield stress of fine-grained (-23 μm) mineral particle slurries of sphalerite, galena, quartz, and kaolinite vary as a function of frame concentration. Note that at low slurry concentrations, the slurry's apparent viscosity and yield stress are similar to those of water, which are very low. However, as the slurry concentration increases, the apparent viscosity of the clay mineral kaolinite begins to increase dramatically. Zhang et al. (Zhang et al., 2021) investigated how the concentration of clay minerals in the slurry affects its rheological properties, observing that clay minerals exert a more pronounced influence on the slurry's apparent viscosity within the same concentration range. The structural network formed by two clay minerals, bentonite and kaolinite, within the flotation slurry, suggests that shear impedes the slurry and increases its viscosity. The apparent viscosities of sphalerite, galena, and quartz exhibited similar trends to changes in yield stress, all increasing with rising slurry concentrations, though quartz showed a comparatively smaller increase. At the same slurry concentration and particle size, the apparent viscosity and yield stress of single-mineral slurries follow this order: kaolinite > sphalerite > galena > quartz. Apparent viscosity measures the slurry's flow resistance as the rotor rotates. A higher apparent viscosity indicates more intense interactions among mineral particles, resulting in greater the resistance to slurry flow. An increase in yield stress signifies that more shear force is required to disrupt the slurry's original stable structure.

### 3.2. Effect of slurry pH on the rheological properties of slurry

The valuable minerals sphalerite and galena, along with the gangue mineral quartz and kaolinite, ionize different metal ions and adsorb trapping agent with varying strengths at different pH levels. This leads to varying interaction forces between mineral particles, which in turn affects the slurry's rheological properties.

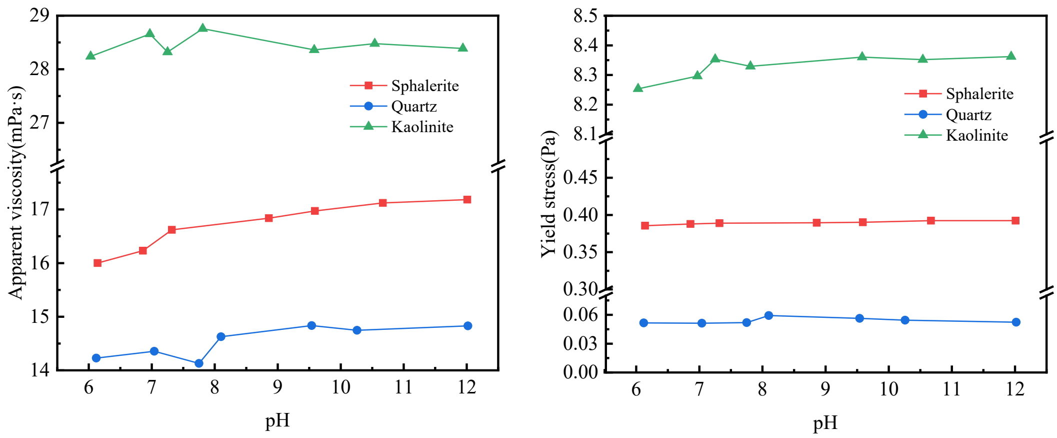


Fig. 8. Apparent viscosity (left), yield stress (right) vs. pH of fine-grained (-23 μm) sphalerite, quartz and kaolinite mineral slurries (butylated yellow dosage of 150 mg/L)

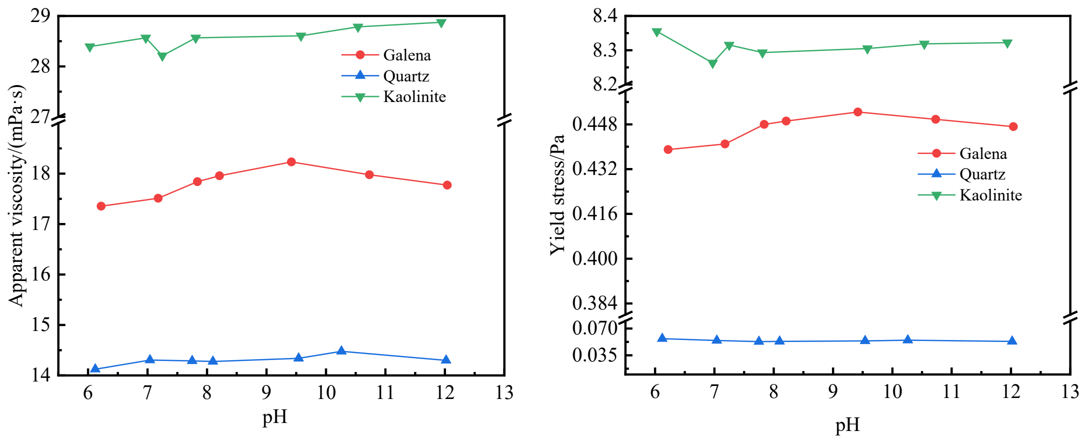


Fig. 9. Apparent viscosity (left), yield stress (right) vs. pH of fine-grained (-23 μm) slurries of galena, quartz, and kaolinite minerals (ethanethione dosage of 150 mg/L)

As shown in Figs. 8 and 9, the apparent viscosity and yield stress of the gangue mineral slurries comprised of kaolinite and quartz, respectively, remained essentially unchanged in the experimental range of pH 6-12. However, the kaolinite slurry exhibited higher apparent viscosity and yield stress. When ethylthiozine and butylxanthan were used as collectors within the pH range 9.0-9.5, the apparent viscosities of the slurries were 28.60 and 28.36 mPa·s, respectively, while the yield stresses were 8.31 and 8.36 Pa, respectively. In contrast, the apparent viscosities and yield stresses of quartz slurries were lower across the entire pH range. When ethylthiozine and butylflavonoid were used as the collectors within a pH range of 9.0-9.5, the slurries' apparent viscosities were 14.34 and 14.83 mPa·s, respectively, with yield stresses of only 0.05 Pa. The apparent viscosity and yield stress of galena and sphalerite were influenced by the effectiveness of the collector. The apparent viscosity and yield stress of galena initially increased and then decreased with rising pH. The highest values for apparent viscosity and yield stress of galena occurred at pH 9.0-9.5, reaching 18.23 mPa·s and 0.45 Pa, respectively. Ethyl sulphide showed the most effective collectorping for galena at pH 9.0-9.5. As pH increased, the apparent viscosity of sphalerite gradually increased, with the rate of increase slowing down over time. At pH 11.5-12.0, the apparent viscosity peaked 17.18 mPa·s, and the yield stress remained largely unchanged. Butylxanthan demonstrated the highest effectiveness in collectorping sphalerite at pH 11.5-12.0.

### 3.3. Effect of collector concentration on rheological properties of sphalerite and galena slurry

The results, which are depicted in Fig. 10, show that changes in collector concentration do not affect the apparent viscosity and yield stress of the solution, as both butylflavaniline and ethylthiazine maintain a constant apparent viscosity of 10 mPa·s and yield stress of and 0 Pa.

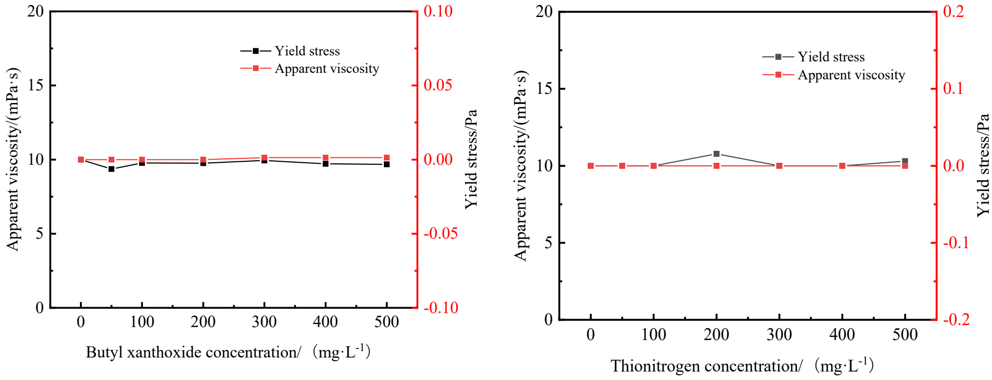


Fig. 10. Apparent viscosity and yield stress of butylxanthine (left) and ethylthiazide (right) solutions at different concentrations

Fig. 11 illustrates the effects of various concentrations of butylated yellowing agent and sodium diethyldithiocarbamate on the slurry's apparent viscosity and yield stress for both valuable minerals and gangue mineral. Increasing concentrations of butylated yellowing agent and sodium diethyldithiocarbamate have similar effects on the apparent viscosity and yield stress of the slurry. As the concentration of the collector increased, its chemical adsorption with sphalerite and galena also increased. Essentially, metal cations on the mineral surfaces combined to form complexes, resulting in the slurry developing a higher apparent viscosity. Without the collector, the apparent viscosities of sphalerite and galena were and 16.01 and 15.93 mPa·s, respectively. In contrast, when the concentration of the collector was 150 mg/L, the apparent viscosities of the sphalerite and galena slurries were 22.04 and 18.05 mPa·s, respectively. Since butylxanthan and ethylthiazide do not impart floatability to the gangue mineral quartz and kaolinite, increasing the collector concentration does not raise the slurry's apparent viscosities. Instead, the viscosities tend to be reduced to some extent.

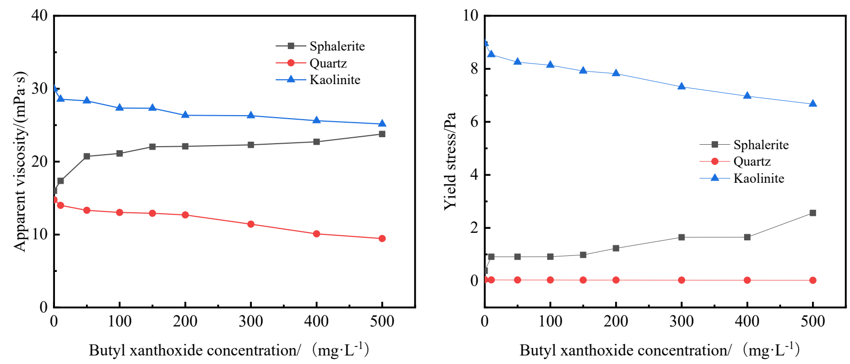


Fig. 11. Effect of different concentrations of butylxanthines on apparent viscosity (left) and yield stress (right) of fine-grained (-23 μm) sphalerite, quartz, and kaolinite slurries (pH 11.5-12.0)

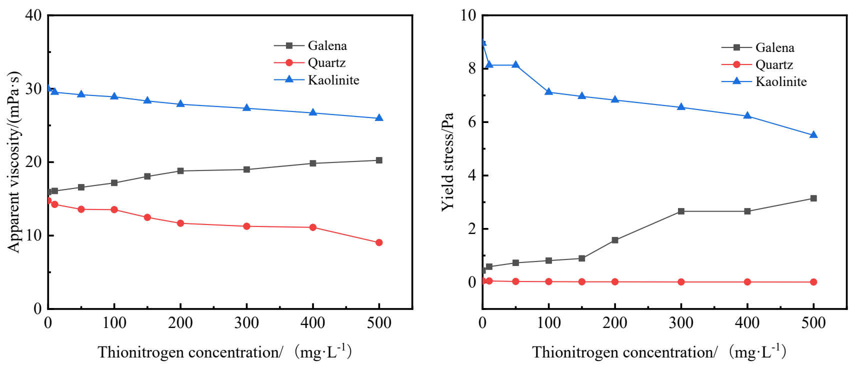


Fig. 12. Effect of different concentrations of sodium diethyldithiocarbamate on apparent viscosity (left) and yield stress (right) of fine-grained (-23 μm) galena, quartz, and kaolinite slurries (pH 9.5-10.0)

Similarly, the yield stresses of fine-grained sphalerite and galena increased significantly with a higher collector concentration. Without the collector, the yield stresses of sphalerite and galena were 0.39 and 0.44 Pa respectively; At a collector concentration of 150 mg/L, the yield stresses increased to 0.92 and 0.89 Pa, respectively. The collector enhanced the hydrophobicity of the sphalerite and galena surfaces, leading to higher yield stresses. The increased hydrophobicity facilitated the formation of complexes upon adsorption, which hindered pulp shear and further raised the yield stress. However, butyl diethyldithiocarbamate and sodium diethyldithiocarbamate did not improve the hydrophobicity of kaolinite and quartz surfaces, resulting in a decrease in the yield stress of the kaolinite and quartz slurries.

Shang et al. (Shang and Sun, 2023) found that at varying octadecylamine concentrations, particles of zincite, kaolinite, and calcite can form agglomerates, leading to an increase in the pulp's apparent viscosity and yield stress. The agglomerate-dispersion behavior among mineral particles can be observed in the slurry using a polarized light microscope. Galena and sphalerite slurries were treated with sodium diethyldithiocarbamate and butyl xanthate as the collectors, respectively. The impact of collector dosage on the microscopic morphology of galena and sphalerite is depicted in Figs. 13 and 14. At a collector dosage of 0 mg/L, galena and sphalerite were evenly dispersed and arranged, with clearly visible outer contour lines between the particles. Upon the addition of sodium diethyldithiocarbamate and butyl xanthate, the gravitational force between particles increased, causing galena and sphalerite mineral particles to adhere together and form particle agglomerates. As the collector dosage increased, the agglomerates grew larger. Compared to dispersed particles, these agglomerates reduced the slurry's fluidity, leading to the slurry developing a higher apparent viscosity and yield stress.

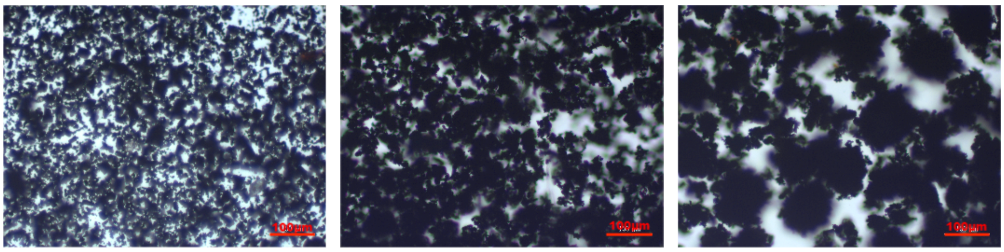

Fig. 13. Microscopic morphology of galena with different sodium diethyldithiocarbamate dosages (0, 150mg/L, 300mg/L)

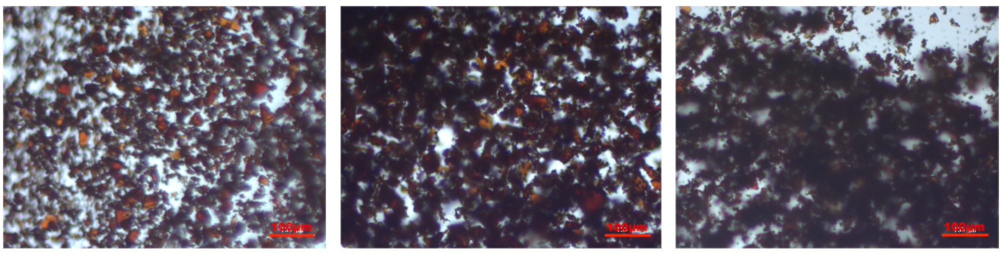

Fig. 14. Microscopic morphology of sphalerite with different amounts of butyl xanthate (0, 150mg/L, 300mg/L)

The statistical results of the particle size distribution of galena and sphalerite particles agglomerated by different collector concentrations are shown in Table 1. Without any collector, the mineral particles were uniformly dispersed in the slurry, with the Dmean of galena and sphalerite being 12.30 μm and 13.02 μm, respectively. The addition of sodium diethyldithiocarbamate and butyl xanthate enhanced the attraction between particles, leading to agglomerate formation. Higher concentrations of the collector intensified the agglomeration of galena and sphalerite, causing their Dmeans to increase to 32.86 μm and 26.36 μm, respectively.

### 3.4. Effect of sodium silicate (rheological control reagent) concentration on slurry rheological properties

In the flotation system for lead and zinc sulfide, sodium silicate acts as a rheological control reagent by inhibiting gangue mineral to enhance flotation selectivity, and also serves as a dispersant.

Table. 1. Particle size distribution of granular aggregates with different amounts of collector

| Sample | collector/ (mg/L) | $D_{10}$/ μm | $D_{50}$/ μm | $D_{90}$/ μm | $D_{mean}$/ μm |
|---|---|---|---|---|---|
| Galena | 0 | 2.61 | 8.57 | 32.09 | 12.30 |
| | 150 | 3.10 | 19.26 | 55.94 | 25.23 |
| | 300 | 4.10 | 26.51 | 71.71 | 32.86 |
| Sphalerite | 0 | 2.88 | 12.36 | 39.15 | 13.02 |
| | 150 | 2.95 | 15.70 | 56.02 | 23.23 |
| | 300 | 3.17 | 16.65 | 66.89 | 26.36 |

The addition of sodium silicate resulted in varying degrees of reduction in the apparent viscosity and yield stress of fine-grained sphalerite, galena, quartz, and kaolinite slurries. Overall, quartz exhibited lower apparent viscosity and yield stress, with minimal change as the sodium silicate concentration increased. In contrast, the sphalerite, galena, and kaolinite slurries showed a significant decrease in apparent viscosity and yield stress with increasing sodium silicate concentration. Without sodium silicate, the apparent viscosities of the sphalerite, galena, and kaolinite slurries were 22.04, 15.93, and 27.32 mPa·s respectively. At a sodium silicate concentration of 80 mg/L, these apparent viscosities decreased to 19.02, 14.86, and 21.89 mPa·s, respectively.

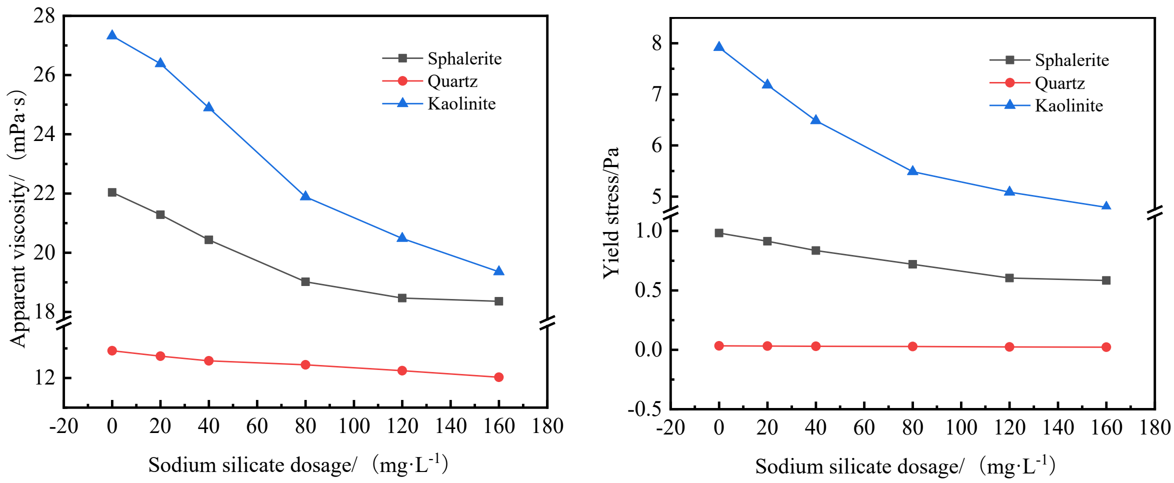


Fig. 15. Effect of Sodium silicate dosage on apparent viscosity (left) and yield stress (right) of different minerals (Butyl xanthate dosage 150 mg/L, pH 11.5-12.0)

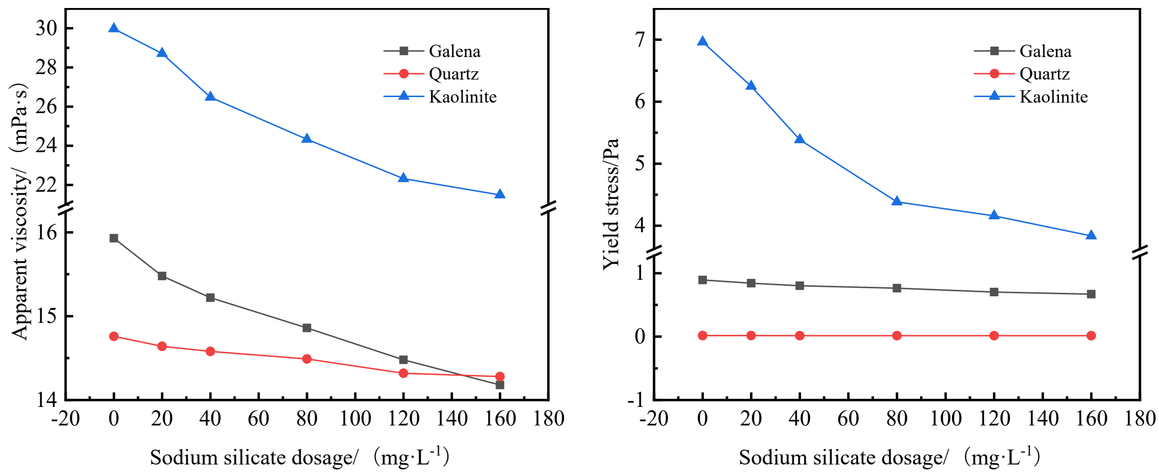


Fig. 16. Effect of sodium silicate dosage on apparent viscosity (left) and yield stress (right) of varying minerals (sodium diethyldithiocarbamate dosage 150 mg/L, pH 9.0-9.5)

Sodium silicate improves the rheological properties of galena and sphalerite, and Figs. 17 and 18 show the impact of sodium silicate dosage on the micro-morphology of galena and sphalerite. Clearly visible in the Figs., the addition of sodium silicate increases the spacing between galena and sphalerite particles, such that microfine particles originally adsorbed on the particles' surface are distinctly outlined. As the amount of sodium silicate increases, the particles become more dispersed, resulting in reduced hindrance to slurry flow. This phenomenon is reflected in the decreased apparent viscosity and yield stress of the slurry.

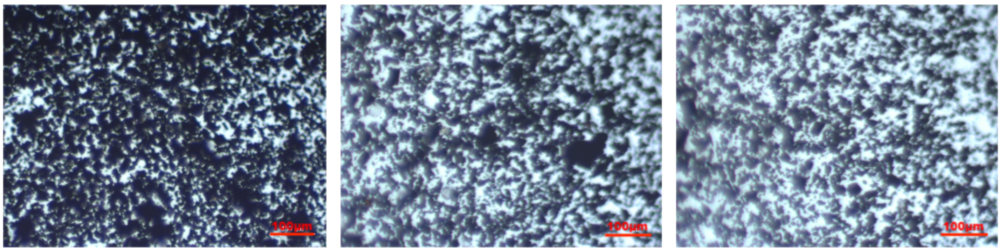

Fig. 17. Microscopic morphology of galena with varying sodium silicate dosages (0, 80mg/L, 160mg/L)

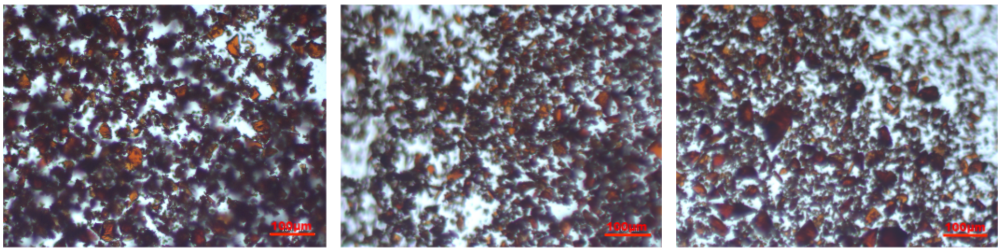

Fig. 18. Microscopic morphology of sphalerite with varying sodium silicate dosages (0, 80mg/L, 160mg/L)

Sodium diethyldithiocarbamate and butyl xanthate in the lead-zinc sulfide ore flotation system exhibit low floatability for the gangue mineral quartz and kaolinite. The microscopic morphology of quartz and kaolinite shows no obvious changes with varying collector dosages. The impact of sodium silicate on the microscopic morphology of the gangue mineral quartz and kaolinite is illustrated in Figs. 19 and 20. Without sodium silicate, fine-grained quartz particles are adsorbed on the surface of larger quartz particles. As the sodium silicate dosage increases, the repulsive force between the particles strengthens, increasing the distance between the particles and dispersing the fine-grained quartz particles marked with distinct outlines. This dispersion is reflected in lower apparent viscosity and yield stress. Without the addition of sodium silicate, kaolinite exhibits a chain structure distribution. Increasing the sodium silicate enhances repulsion between particles, causing the chain structure to break down. As a result, the kaolinite particles disperse and arrange themselves, leading to a rapid decrease in the slurry's apparent viscosity and yield stress, which improves the slurry's fluidity.

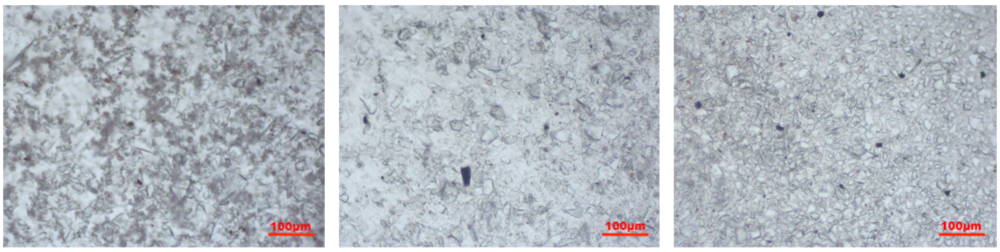


Fig. 19. Microscopic morphology of quartz with varying sodium silicate dosages (0, 80mg/L, 160mg/L)

### 3.5. Influence of gangue content on the slurry's rheological properties and flotation separation

Sodium diethyldithiocarbamate and Butyl xanthate served as the collectors for galena and sphalerite, respectively, at a slurry concentration of 28.57 wt%. Fine-grained (-23 μm) minerals were selected to create binary mixtures of galena-kaolinite, galena-quartz, sphalerite-kaolinite, and sphalerite-quartz. The apparent viscosities of these mixed slurries were measured and the results are depicted in Fig. 21.

Conversly, the apparent viscosity of the mixed ore slurry decreased with increasing quartz content, which is attributed to the difference in rheological properties between kaolinite and quartz minerals.

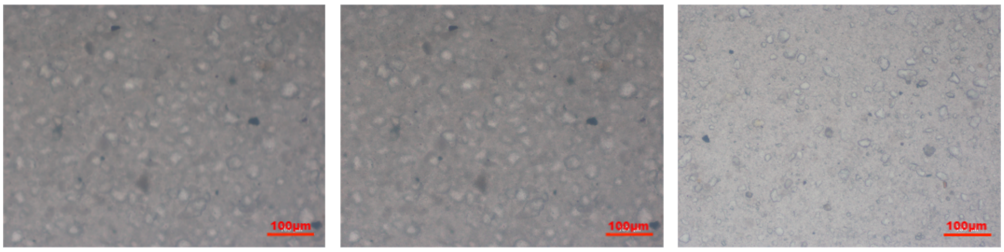


Fig. 20. Microscopic morphology of kaolinite with varying sodium silicate dosages (0, 80mg/L, 160mg/L)

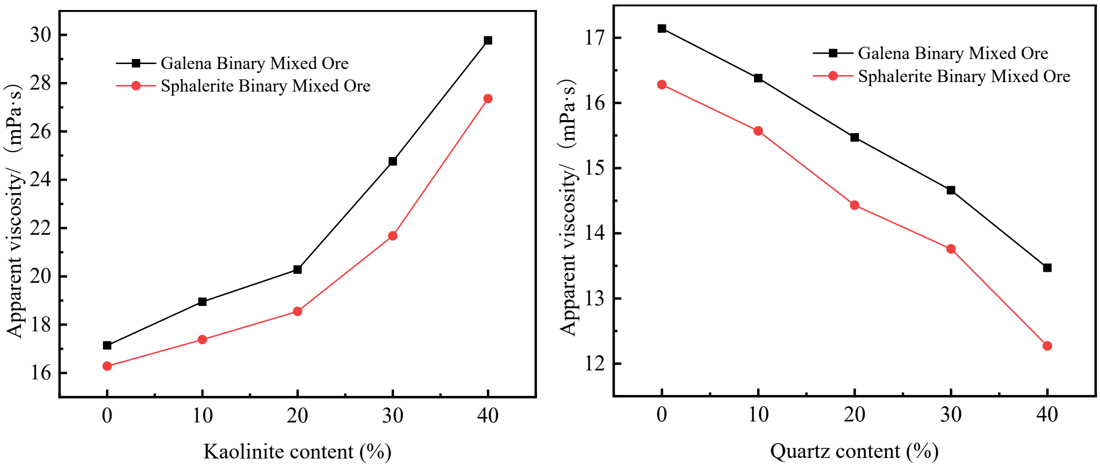


Fig. 21. Effect of gangue content on the apparent viscosity of binary mixed ore slurries (left: kaolinite; right: quartz)

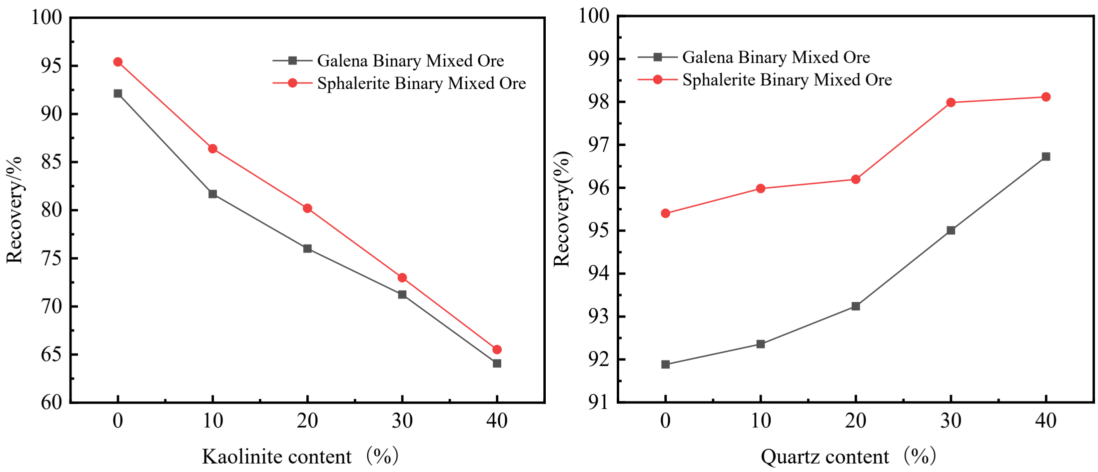


Fig. 22. Effect of gangue content on the recovery rate of binary mixed ore slurries (left: kaolinite; right: quartz)

The flotation results under the aforementioned conditions are illustrated in Fig. 22. In the binary system containing kaolinite, recovery of the valuable minerals (galena/sphalerite) decreased significantly as the relative content of kaolinite in the slurry increased. This decrease can be attributed to the slurry's higher apparent viscosity in response to the higher kaolinite content, which hinders the flotation separation of the valuable minerals (galena/sphalerite). Conversly, in the binary system with quartz, recovery of the valuable minerals (galena/sphalerite) slightly increased as a function of increasing quartz content in the slurry. This outcome is attributed to the slurry's lower the apparent viscosity with increasing quartz content, suggesting that lower apparent viscosity is advantageous for the flotation of the valuable minerals (galena/sphalerite) in the binary system.

Under the action of kaolinite, the slurry is prone to particle aggregation, which increases the apparent viscosity and yield stress of the slurry, resulting in the sulfide ore-bubble combination is easily disturbed by a large number of network structures in the process of rising, on the one hand, due to the increase in viscosity of the slurry caused by the decline in the flotation rate, on the other hand, the bubbles carrying sulfide ore particles are prone to be mixed with kaolinite and other vein particles during the process of breaking through the network structures, thus leading to a decrease in selectivity. The selectivity decreases as a result of the pulsed stone particles. The attraction between particles is relatively weak and easily dispersed under the action of shear flow field, which has a low influence on the flotation kinetic environment and foam entrainment.

## 4. Conclusions

The apparent viscosity and yield stress of sphalerite, galena, quartz, and kaolinite slurries were examined across varying particle sizes and slurry concentrations, slurry pH levels, collector dosages, and rheological control reagent sodium silicate concentration through slurry rheological testing. Based on the observations of particle agglomerate morphology at different collector and sodium silicate concentrations obtained herein, the following conclusions can be drawn:

(1) In deionized water, the apparent viscosity and yield stress of sphalerite, galena, kaolinite, and quartz slurries increased as particle size decreased. Among slurries with the same particle size, the apparent viscosity and yield stress trended as follows: kaolinite > galena > sphalerite > quartz.

(2) The apparent viscosity and yield stress of the kaolinite slurry sharply increased with rising slurry concentration. Quartz exhibited lower apparent viscosity and yield stress across the entire concentration range, indicating favorable rheological properties, while galena and sphalerite showed intermediate trends. As the concentration increased, the rheological behavior of the four slurries shifted from Newtonian to non-Newtonian fluid.

(3) The apparent viscosity and yield stress of quartz and kaolinite slurries remained largely unaffected by the slurry's pH when influenced by the collector. In contrast, galena and sphalerite are impacted by the presence of the collector. As the collector concentration increases, galena and sphalerite particles tend to agglomerate, which promotes the floatation of lead and zinc minerals. Using sodium diethyldithiocarbamate, galena shows the most pronounced aggregation phenomenon at pH 9.0-9.5 and sphalerite at pH 11.5-12.0.

(4) The rheological properties of the four mineral slurries improved with the addition of sodium silicate as an adjuster. The particles disperse more effectively, with kaolinite showing the most significant improvement in rheology, followed by galena and sphalerite. Quartz is least affected by sodium silicate due to its inherently lower apparent viscosity and low yield stress.

(5) Adding kaolinite increases the apparent viscosity of the galena/sphalerite binary mixed slurry. Excessive apparent viscosity indicates a deterioration in the rheological properties of the mixed slurry, which hampers the flotation separation of the valuable minerals. In contrast, quartz reduces the apparent viscosity of the binary mixed slurry, promoting favourable conditions for flotation separation.

## References

BARNES H.A., HUTTON J.F., WALTERS K., 1989. *An introduction to rheology*. Journal of Non-Newtonian Fluid Mechanics, 3: 199.

VERLAG D.S., ISSN D., 1979. *Shear viseosity of settling suspensions*. Rheologica Acta, 296(18): 289–296.

BOGER D.V., 2000. *Rheology and the minerals industry*. Mineral Procesing and Extractive Metallurgy Review, 20(1): 1-25.

FARROKHPAY S., MORRIS G.E., FORNASIERO D., ET AL., 2005. *Influence of polymer functional group architecture on titania pigment dispersion*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 253(1-3): 183-191.

BECKER M., YORATH G., NDLOVU B., ET AL, 2013.. *A rheological investigation of the behaviour of two Southern African platinum ores*. Minerals Engineering, 49: 92-97.

SHI F N, NAPIER-MUNN T J., 2002. Effects of slurry rheology on industrial grinding performance [J]. International Journal of Mineral Processing, 65(3-4): 125-140.

HE M, WANG Y, FORSSBERG E., 2004. S*lurry rheology in wet ultrafine grinding of industrial minerals: A review*[J]. Powder Technology, 147(1–3): 94–112.

WANG L, LI C., 2020, *A brief review of pulp and froth rheology in mineral flotation*. Journal of Chemistry, 2020: 1-16.

SONG S, LOPEZ-VALDIVIESO A, REYES-BAHENA J L, ET AL, 2001. *Floc flotation of galena and sphalerite fines*. Minerals Engineering, 14(1): 87-98.

ZENG G, ZHU Y, CHEN W., 2023. *A Brief Review of Micro-Particle Slurry Rheological Behavior in Grinding and Flotation for Enhancing Fine Mineral Processing Efficiency*[J]. Minerals, 13(6): 792.

FARROKHPAY S., 2012. *The importance of rheology in mineral flotation: A review*. Minerals Engineering, 36-38: 272-278.

ZHAO F G., 2007. *The present situation of the concentration of Pb-Zn ore*. Non-ferrous Mining And Metallurgy, 23(6): 20-25.

FENG Q, WEN S., 2017. *Formation of zinc sulfide species on smithsonite surfaces and its response to flotation performance*[J]. Journal of Alloys and Compounds, 709: 602-608.

CHEN Y, CHEN J, GUO J., 2010. *A DFT study on the effect of lattice impurities on the electronic structures and floatability of sphalerite*[J]. Minerals engineering, 23(14): 1120-1130.

HINTIKKA V V, LEPPINEN J O., 1995. *Potential control in the flotation of sulphide minerals and precious metals*[J]. Minerals Engineering, 8(10): 1151-1158.

MUSTER T H, PRESTIDGE C A., 1995. *Rheological investigations of sulphide mineral slurries*. Minerals Engineering, 8(12): 1541-1555.

CRUZ N, FORSTER J, BOBICKI., 2019. *Slurry Rheology in Mineral Processing Unit Operations-A Critical Review*[J]. The Canadian Journal of Chemical Engineering, 76.

DAS K, KELLY N, MUIR M., 2010. *Rheological behaviour of lateritic smectite ore slurries*[ Minerals Engineering, 24(7).

MUELLER, S., LLEWELLIN, B., E.W., 2009. *The rheology of suspensions of solid particles*. Proc.R. Soc. 39, 291–300.

NESTOR CRUZ, JOHN FORSTER, ERIN R. BOBICKI., 2019. *Slurry rheology in mineral processing unit operations: A critical review*.The CanadianJournal of Chemical Engineering, 2019 (7).

GUSTAFSSON J, MIKKOLA P, JOKINEN M, ET AL., 2000. *The influence of pH and NaCl on the zeta potential and rheology of anatase dispersions*[J].Colloids and Surfaces A: Physicochemical and Engineering Aspects, 175(3): 349-359.

CHEN X, PENG R., 2008. *Pb-Zn metal resources condition and strategy for Pb-Zn metals industry sustainable development in China*. Non-ferrous Metals, (3):129-132 .

GUPTA V, HAMPTON M A, STOKES J R, ET AL., 2011. *Particle interactions in kaolinite suspensions and corresponding aggregate structures*. Journal of Colloid and Interface Science, 359(1): 95-103.

WANG C, ZHANG Q, MAO S, ET AL., 2020. *Effects of fine minerals on pulp rheology and the flotation of diaspore and pyrite mixed ores*. Minerals, 10(1): 60.

MONTALTI M, FORNASIERO D, RALSTON J., 1991. *Ultraviolet-visible spectroscopic study of the kinetics of adsorption of ethyl xanthate on pyrite*. Journal of Colloid and Interface Science, 143( 2) : 440-450.

PAPO A, PIANI L, RICCERI R., 2002. *Sodium tripolyphosphate and polyphosphate as dispersing agents for kaolin suspensions: rheological characterization*. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 201(1-3): 219-230.

CRUZ N, PENG Y, ELAINE W., 2015. *Interactions of clay minerals in copper-gold flotation: Part 2 - Influence of some calcium bearing gangue minerals on the rheological behaviour*. International Journal of Mineral Processing, 141.

ZHANG M, PENG Y., 2015. *Effect of clay minerals on pulp rheology and the flotation of copper and gold minerals*. Minerals Engineering, 70: 8-13.

CHEN, PENG., 2018. *Managing clay minerals in froth flotation – A critical review*.Informa UK Limited;Taylor & Francis.

ZHANG L, GAO J, KHOSO S A, ET AL., 2021. *A reagent scheme for galena/sphalerite flotation separation: Insights from first-principles calculations*. Minerals Engineering, 167: 106885.

SHANG Y, SUN C., 2023. *Effects of physical and physico-chemical factors on pulp rheology of smithsonite*. Physicochemical Problems of Mineral Processing, 59.