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Application of dodecyl amine/dodium petroleum sulfonate mixed collector in quartz-feldspar flotation separation

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Abstract: It's highly challenging to separate feldspar from quartz by flotation owing to their similar crystal structure and physicochemical properties. Using mixed collectors has become a promising method to improve the quartz-feldspar separation. In this study, mixed dodecyl amine (DDA) and sodium petroleum sulfonate (SPS) surfactants were used in the flotation separation of feldspar and quartz, and the adsorption mechanism of mixed collectors and depression mechanisms of two depressants were investigated through zeta potential, contact angle and Fourier transform infrared (FT-IR) spectra. When the pH reached 4.5, the separation of feldspar from quartz was more obvious. In the presence of DDA/SPS collector, the contact angle of feldspar was increased more obviously leading to enhance hydrophobicity. The infrared spectra revealed the interaction of collectors on feldspar surface involved physical and chemical adsorption, whereas the adsorption of collector on quartz was only physical interactions. The use of sodium hexametaphosphate resulted in a significantly enhanced separation performance. The weaker physical adsorption of mixed collector on quartz can be destroyed by sodium hexametaphosphate. This study is beneficial for understanding the collect mechanisms of mixed cationic-anionic surfactants on quartz and feldspar minerals, and promotes the development of advanced feldspar separation techniques.

Keywords: quartz, feldspar, flotation, collector, depressor

1. Introduction

Quartz and feldspar are widespread minerals in the world, wherein feldspar make up as much as 60% of the earth's crust (Ding et al., 2023, Shen et al., 2023). Feldspar is widely used in glass, ceramics, enamel frits, and paint industries, etc (Zhang et al., 2018, Montiel-Anaya and Franco., 2019, Liu et al., 2021). However, feldspar is often associated with quartz in nature, which results in a low purity and limits its applications (Sun et al., 2023). The beneficiation of low-grade feldspar ores is thus extremely critical. Given the fact that feldspar and quartz show similar physical and chemical properties, it is difficult to separate feldspar from quartz by conventional gravity separation, magnetic separation, scrubbing and classification. Currently, flotation is the most feasible method to separate feldspar from quartz, while the non-selectivity of electrostatic adsorption of widely used cationic collectors (e.g., amines) on feldspar and quartz makes the flotation process low efficiency (Xu et al., 2023).

To improve the flotation separation of feldspar from quartz, many studies have emphasized on innovative flotation reagents (Ding et al., 2023, Larsen and Kleiv., 2016, Perry et al., 1983, Heyes et al., 2013). Conventionally, the use of HF in the feldspar-quartz separation was considered as the most efficient reagent (Larsen and Kleiv., 2016). Furthermore, feldspar floated from quartz using long-chain alkyl cationic amine surfactants or mixed anion-cation surfactants as collectors also have achieved excellent results under highly acidic conditions (Sun et al., 2020, Lou et al., 2016, Heyes et al., 2013, Wen

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et al., 2003). Liu et al proposed that the mixed use of anionic and cationic surfactants can improve the flotation selectivity of feldspar from quartz, because anionic surfactants play an activating role like that of regulators and result in the different amine adsorption capacities of on mineral surfaces (Liu et al., 1993). Therefore, it is of great significance to develop new mixed collectors for the high-efficiency feldspar-quartz separation. As an anionic surfactant, the structural composition of sodium petroleum sulfonate is relatively complex (Bai et al., 2010). It is widely used in the flotation of iron oxide minerals and non-metallic minerals (Zhu et al., 2015). However, there are currently few reports on the use of petroleum sulfonates as anionic collectors for the flotation separation of quartz and feldspar.

Another issue related to feldspar-quartz separation is the development of efficient and selective depressants, in weak acidic pulp. There are very few studies on depressants for flotation separation of quartz and feldspar (Feng et al., 2018). Usually, depressants were used to suppress feldspar under alkaline conditions, thereby recovering quartz (Liu et al., 2018). Sodium silicate (SS) and sodium hexametaphosphate (SHMP) are commonly used as inorganic depressant (Wang et al., 2020, Chen et al., 2019, Gan et al., 2009). Both sodium hexametaphosphate and water glass can inhibit quartz under acidic conditions, but when the pH of the solution is too high, sodium hexametaphosphate will lose its effect and this depressant effect will disappear (Gan et al., 2009).

Previous studies have shown that mixed anionic and cationic surfactants are more efficient in separating quartz and feldspar in strongly acidic environments. Considering the corrosion of equipment and water treatment issues caused by strong acidic environments, in the study, the new mixed collector dodecyl amine (DDA)/sodium petroleum sulfonate (SPS) for efficient flotation separation of feldspar and quartz under weak acidic conditions. In addition, the SHMP and SS were employed to separate feldspar from quartz. The adsorption mechanism of reagents was illustrated by contact angle analysis, zeta potential tests, Fourier-transform infrared (FT-IR) spectra, and solution chemistry.

2. Materials and methods

2.1. Materials

The chemical analysis of pure quartz (Q) and feldspar ore (F) showed that the quartz purity was more than 99% and the feldspar purity was about 96%. The results of XRF analysis on the pure minerals of quartz and feldspar used in the experiment are shown in Tables 1 and 2. From Table 1 and Table 2, the SiO_2 content in quartz reached 99.94%, and the Al_2O_3, K_2O, Na_2O, and SiO_2 contents in feldspar were 10.77%, 3.59%, 64.79%, and 18.70%, respectively, suggesting high purities of quartz and feldspar samples. The single minerals applied in the experiment were crushed to smaller sizes. The sample range -0.074 mm to +0.045 mm was used for flotation, while the fines (-5 µm) were used in zeta potential and FTIR measurements.

The mixed mineral sample at the weight ratio of 1:4 (F: Q) was packed into the flotation tank with the volume of 100mL. 10.0 g sample was mixed with deionized water at 1600 rpm impeller speed in all tests. Percent solids by weight and pH of 4.5 were kept constant in all experiments. The pH was first adjusted by H_2SO_4 solution, followed by stirring for 2 min, and then the depressant and collector were added into the cell in sequence. The floatation time of 3 min was selected. The froth product was tested and analyzed to calculate the flotation recovery.

Table 1. XRF results of quartz

Element	SiO_2	Al_2O_3	Fe_2O_3	CaO	TiO_2	As_2O_3
wt%	99.94	0.018	0.002	0.16	0.002	0.019

Table 2. XRF results of feldspar

Element	SiO_2	Al_2O_3	K_2O	Na_2O	Fe_2O_3	CaO
wt%	64.79	18.70	10.77	3.59	0.08	0.77

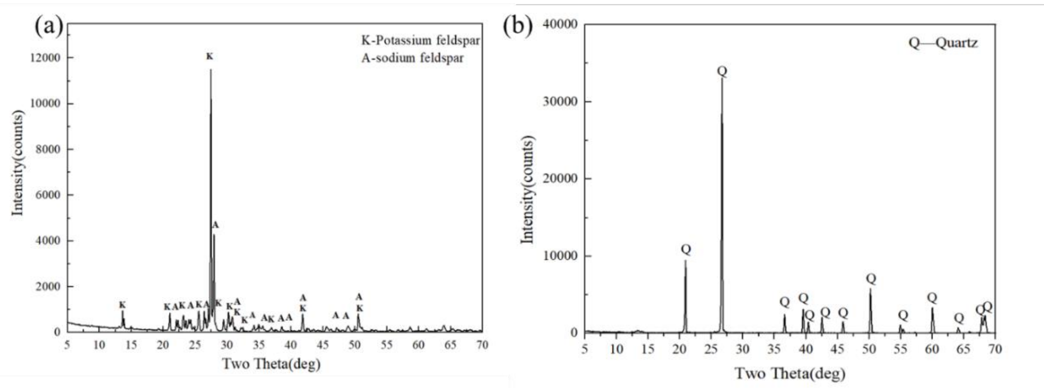

Fig. 1. XRD patterns of feldspar (a)and quartz (b)

2.2. Reagents

The collectors of DDA and SPS (No. PSK-47) was supplied by Sinopharm Group Co., Ltd and PetroChina Karamay Petrochemical CO., Ltd, respectively. Sodium hexametaphosphate (SHMP) and acid sodium silicate (SS) were obtained from Kaifeng Dongda Chemical CO., Ltd. Analytical grade H_2SO_4 and NaOH were used for pH adjustment, and deionized water was used in all experiments.

2.3. Analysis methods

The qualitative analysis in the single mineral preparation were performed using an X-ray fluorescence (XRF) diffractometer (PANalytical.B. V, Netherlands) incorporation. Fourier-transform infrared (FT-IR) spectra were measured using Nexus (Thermo Fisher Scientific Inc., Waltham, MA, USA). Further, the zeta potential was measured with a Nano-ZS90 analyzer (Malvern Co., Malvern, UK). The wetting properties of solid mineral samples were characterized under laboratory conditions by a JC2000C1 contact angle measuring instrument (Shanghai Zhongchen digital technology equipment Co., China).

2.3.1. Contact angle measurements

Take the minerals and reagents used in the flotation test, mix and stir in the flotation tank for 10 minutes, then filter with filter paper and air dry naturally; Take a small amount of ore sample and place it into a special contact angle mold for pressing, and take the average of three tests for each condition as the final result.

2.3.2. Zeta potential measurements

The experiment used the Nano-ZS90 Zeta potential meter to measure the mineral Zeta potential. The feldspar and quartz samples were ground to the submicron level, and 0.05 g of the ore sample was weighed. 50 mL of 1 mM KCl solution was added, with a slurry concentration of 0.1%. The pH value of the slurry was adjusted, and the reagent solution was added in order of the flotation test concentration and order. The mixture was stirred evenly for 10 minutes and left to stand for 10 minutes before testing. The average of three tests under each condition was taken as the result.

2.3.3. FT-IR analysis

Take ultra-fine samples (-10μm) interact with medication and dry under low temperature conditions. And thoroughly dry the KBr reagent powder, mix it evenly with a small amount of sample to be tested (with a mass ratio of 1:100 between ore and reagent), and put it into a grinding tool. Press it into a transparent round thin plate through the pressing method for testing.

2.3.4. Flotation results

This paper evaluates the flotation separation effect by calculating the recovery rate of Al_2O_3 in the flotation foam (A) and the beneficiation efficiency(B). The calculation formula is as follows:

$$A=r\cdot\frac{\beta}{\alpha}\times100\% \quad (1)$$

$$B=\frac{A-r}{1-{\alpha}/{\beta_x}}\times100\% \quad (2)$$

where r is concentrate yield, α is grade of Al_2O_3 in mixed ore, β is grade of Al_2O_3 in concentrate and β_x is grade of Al_2O_3 in pure feldspar.

3. Results and discussion

3.1. Single mineral flotation

The DDA and SPS are used as collectors, with the ratio of 3:1 for anionic and cationic collectors. Experiments were conducted using H_2SO_4 to adjust pH of 2.5, 3.5, 4.5, 5.5, 6.5, and 7.5. The flotation results are shown in Table 3.

Table 3. Single mineral flotation results

pH	rate of recovery/%		D-value/%
	Fledspar	Quartz	
2.5	24.79	5.66	19.13
3.5	65.69	5.25	60.44
4.5	75.53	4.07	71.46
5.5	73.75	83.23	-9.48
6.5	33.60	93.79	-60.19
7.5	32.42	64.28	-31.86

From Table3, in the pH range of 2.5-7.5, the recovery rate of feldspar shows a trend of first increasing and then decreasing, and reaches its maximum value at 4.5. Under acidic conditions (pH ≤ 4.5), the recovery rate of quartz is relatively low. When the pH reaches 5.5 or even higher, the recovery rate of quartz increases sharply. In summary, it can be concluded that at pH of 4.5, the mixed collector DDA+SPS has a good flotation separation effect on quartz and feldspar, with a recovery difference of 71.46%.

3.2. Mixed flotation tests

3.2.1. Effect of pH

The effect of pH on quartz-feldspar flotation is shown in Fig. 1, the dosages of DDA and SPS both were 30 mg/L.

From Fig. 2, it can be seen that as the pH increases, the grade of Al_2O_3 always decreases, especially in the pH range of 3.5-5.5. The recovery rate of Al_2O_3 and the beneficiation efficiency both increase first and then decrease. The recovery rate of Al_2O_3 reaches its highest point at pH 5.5, while the

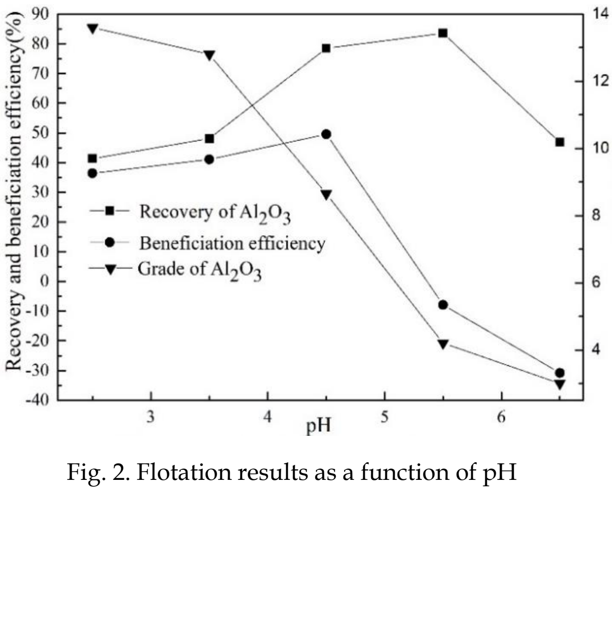

Fig. 2. Flotation results as a function of pH

beneficiation efficiency reaches its highest point at pH 4.5. The results show that feldspar floated substantially while quartz had no floatability within the acidic pH of 2.5-4.5. In this pH region, the recovery nearly was maximum (about 80%) when pH was 4.5. However, above pH 4.5, the Al_2O_3 content of concentrate dropped sharply due to both minerals had similar flotation response. Under this condition, it was not conducive to float feldspar selectively.

3.2.2. Effect of SPS/DDA ratio

The effect of SPS/DDA ratio on the flotation of quartz-feldspar is displayed in Fig. 3. The concentration of DDA was fixed at 40 mg/L, and the amount of anionic collector (SPS) varied from 20 to 120 mg/L. As can be seen from Fig. 3, at the condition of 120 mg/L SPS (SPS/DDA ratio = 3), the values of recovery and grade of feldspar were better that those obtained at lower SPS/DDA ratios. The results demonstrate that feldspar can be floated selectively from quartz at the pH of 4.5, with high SPS/DDA ratios.

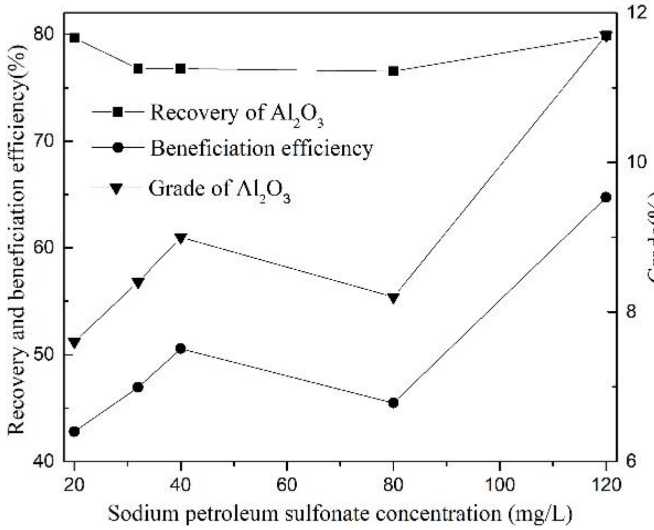

Fig. 3. Flotation results as a function of SPS concentration, pH value of 4.5

3.2.3. Effect of mixed collector dosage

The effect of the dosage of mixed collector on the flotation effect under the condition of pH value of 4.5 and a SPS/DDA ratio of 3 was depicted in Fig. 4.

As shown in Fig. 4, with the increase of pH, the beneficiation efficiency and Al_2O_3 grade first decrease, reaching the lowest point at 120mg/L, and then reaching the highest point when the dosage is increased to 160mg/L. However, with an increase in dosage, both slightly decrease. With the increase of collector concentration, the recovery rate of Al2O3 shows an upward trend. When the collector concentration is 160mg/L, that is, under the conditions of 40mg/L DDA and 120mg/L SPS, the recovery rate is the highest, about 80%, and the Al_2O_3 content in the concentrate can reach about 12%. When reaching this concentration, quartz undergoes negligible flotation. The results indicate that the mixed addition of DDA and SPS can achieve the separation of feldspar and quartz.

3.2.4. Effect of depressant concentration

The effect of depressant concentration at a SPS/DDA ratio of 3 on the feldspar flotation for is presented in Fig. 5, with pH value of 4.5. The results show that sodium hexametaphosphate had positive effect on the flotation at the concentration of 50 mg/L with the Al_2O_3 content of 15%, and the recovery of about 65%. Whereas, acid sodium silicate was nearly ineffective at the same concentration, when up to the concentration of 100 mg/L, the Al_2O_3 content was 14%. It can be concluded that the inhibition effect of sodium hexametaphosphate is better, which can restrain quartz at low dosage, and increase the grade of feldspar by 3% under the best conditions. Nevertheless, the inhibition ability of acid sodium silicate was poorer and the consumption was twice of that of sodium hexametaphosphate. These results clearly demonstrate that a mixture of DDA+PAK-47+sodium hexametaphosphate was a better reagent regime for feldspar minerals.

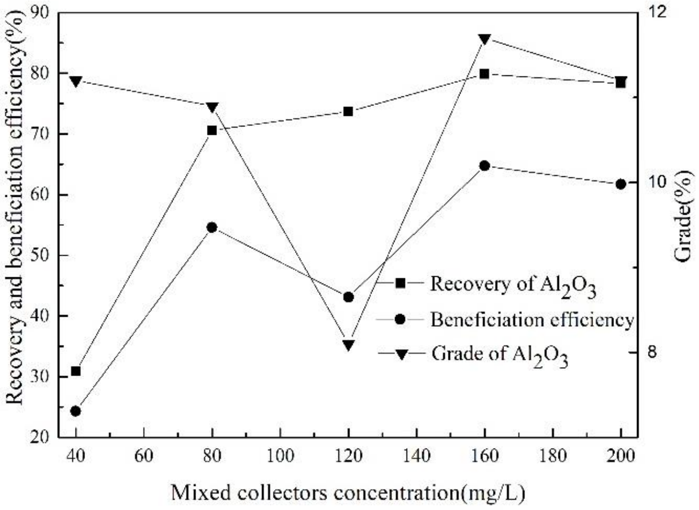

Fig. 4. The flotation responses as a function of the mixed collector concentration at pH value of 4.5

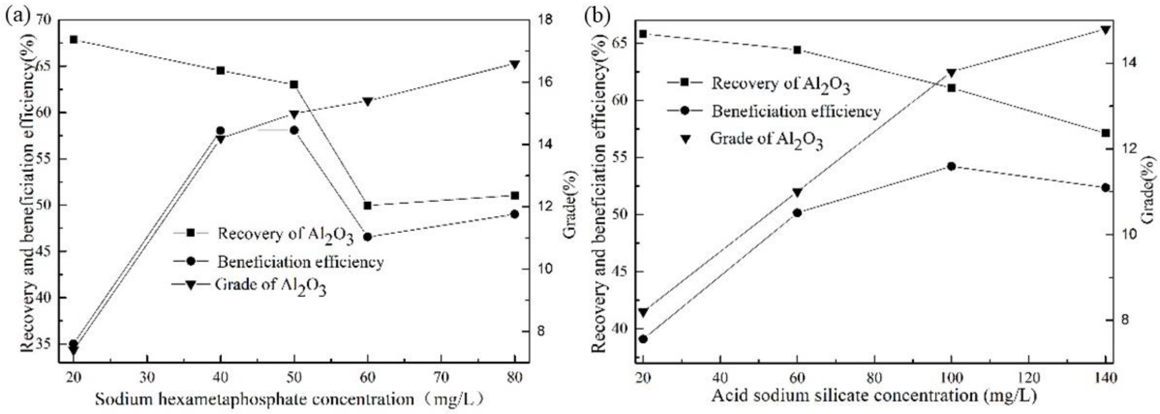

Fig. 5. The effect of (a) sodium hexametaphosphate, (b) acid sodium silicate on the flotation of feldspar-quartz

3.3. Mechanism of action of mixed collector and depressants

At the end of the flotation tests, which mixture ratio of DDA/SPS was determined as optimum. So, in all mechanism analysis sections, the ratio of DDA and SPS used is the optimal ratio for flotation experiments, i.e. DDA: SPS=1:3.

3.3.1. Hydrophobic characteristics

The contact angles have been generally used to evaluate the degree of hydrophobicity and wettability of minerals(MYERS D., 1999). The effect of the concentration of the mixed collector on the contact angle is depicted in Fig. 6, the concentration is varied from 40 to 200 mg/L.

Fig. 7 shows that the contact angles of feldspar increased with the concentration of mixed collector increased from 40 to 160 mg/L. Further improving the collector concentration to 200 mg/L of mixed collector led to a slight decrease of the contact angles of feldspar. Differently, the contact angles of quartz increased with the concentration of mixed collector increased from 40 to 200 mg/L, but the overall contact angles of quartz were lower than those of feldspar at different collector dosage. Thus, a collector concentration of 160 mg/L was used to further analyze the depressants on the wettability of minerals.

To further investigate the wetting behaviors of the collector and depressants on minerals, the contact angles were examined at a pH of 4.5, with the results presented in Fig. 6. Fig. 6 shows that the contact angle of pure feldspar is smaller compared with that of quartz. The smaller the contact angle is, the better wetting of the mineral and the higher the hydrophilic efficiency. In the case of the DDA+PSK-47 collector, it is evident that the contact angle of feldspar and quartz minerals sharply increases, and the former obtain a bigger value, which indicate the mixed solution of DDA+PSK-47 (1/3) can make the feldspar surface hydrophobic, and the two surfactants are able to co-adsorb onto a feldspar surface to yield the better collecting capacity. The addition of sodium hexametaphosphate had little effect on the contact angle between quartz and feldspar. However, acid sodium silicate reduced the contact angle of quartz, it also slightly reduced the contact angle of feldspar.

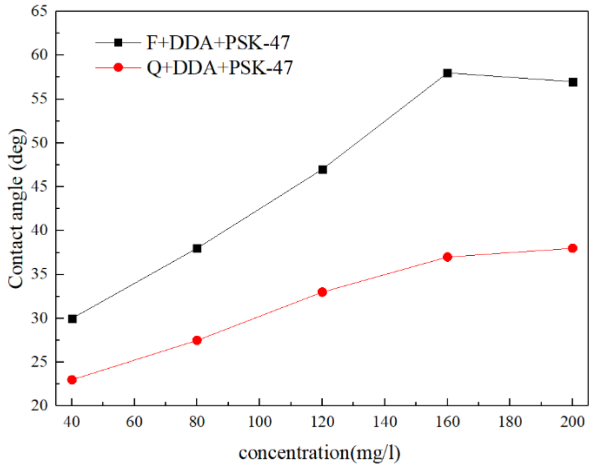

Fig. 6. Contact angle of minerals as a function of mixed collector concentration

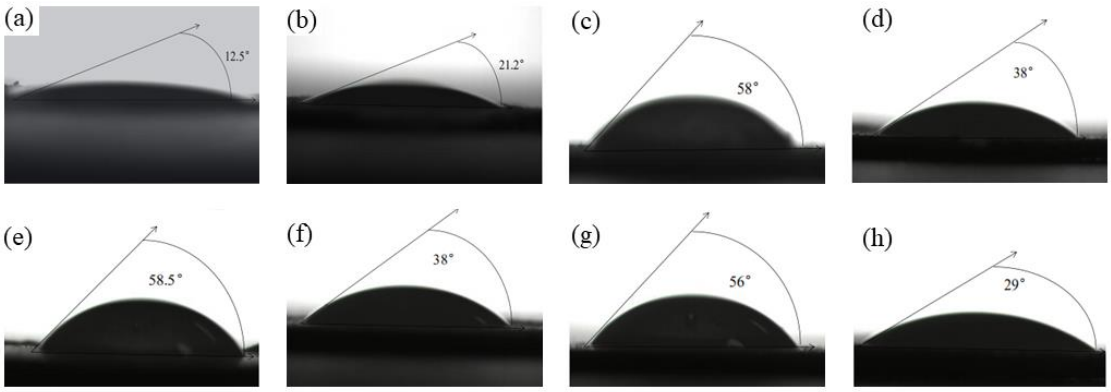

Fig. 7. The contact angles of minerals (a) F, (b) Q, (c) F+DDA+PSK-47, (d) Q+DDA+PSK-47, (e) F+DDA+PSK-47+ sodium hexametaphosphate, (f) Q+DDA+PSK-47+ sodium hexametaphosphate, (g) F+DDA+PSK-47+ acid sodium silicate, (h) Q+DDA+PSK-47+ acid sodium silicate

3.3.2. Zeta potential studies

The zeta potential of quartz and feldspar as a function of pH at deionized water and the mixed solution of cationic-anion surfactants is presented in Fig. 8. The two pure minerals are negatively charged throughout the entire pH. The extrapolation of the curves shows that the isoelectric point of quartz is at about pH 2, the isoelectric point of feldspar is below pH 2, and feldspar exhibits more negative charge down to pH 2, which is in good agreement with the reported literature (Kangal et al., 2017, Tsuyoshi,er al., 2011, Aba Ka-Wood et al., 2016, Kursun., 2010). It is believed that the feldspar mineral is a mixture of Al–O bonds and Si–O bonds, so the charge state of the surface should be the comprehensive reflection of alumina and silica units (Liu et al., 2013). The solution of K+, Na+ on the cleavage plane leaves a negative lattice and active Si–OH and SiO- regions, leading to a lower zeta potential than quartz. Previous results showed that the solutions containing cationic–anionic surfactants can interact resulting in complexes or precipitates (Panandiker et al., 2015, Lu et al., 2013). The zeta potential increases towards the positive direction due to the forming complex is positively charged (Fig. 8). Whereas, the surface potential of the feldspar mineral was significantly enlarged, and the adsorption capacity of surfactants was much larger at pH 4.5. The co-adsorption of sulfonate together with DDA increased the hydrophobicity, thus increasing flotation response of feldspar. Since the feldspar mineral contains Al^{3+} adsorption sites, the surfactants possess negative sulfonate species and positive amine groups, based on the surface charge of minerals and solution conditions, the functional species could adsorb through electrostatic interactions and chemisorb on Al3+ sites, thereby leading to the flotation of feldspar but little adsorbed on quartz.

The influence of depressants on zeta potentials of mineral-collector systems is shown in Fig. 9. The results illustrate that the collectors had similar influence on both quartz and feldspar zeta potentials. The similar adsorption behavior of mixed collectors at pH 4.5 is attributed to the fines (-5μm) used in zeta-potential, owing several broken bonds (Vidyadhar et al., 2007). It is important to note that the only distinction between these studies lies in the fact that a coarser size fraction (-0.74+0.45 mm) was employed in the flotation tests while the fines (-5μm) were conducted in zeta-potential studies. However, adding the sodium hexametaphosphate and acid sodium silicate, feldspar exhibit relatively more negative potentials compared to the zeta potentials of quartz at the same condition.

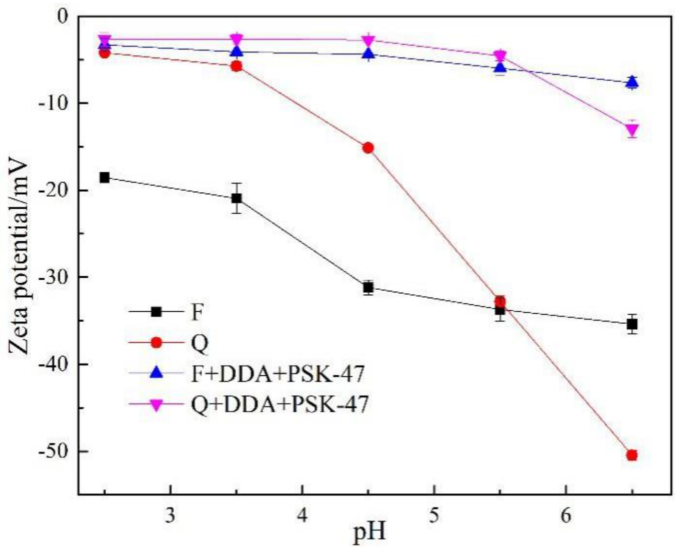

Fig. 8. Zeta potential of minerals as a function of pH value at two different solutions

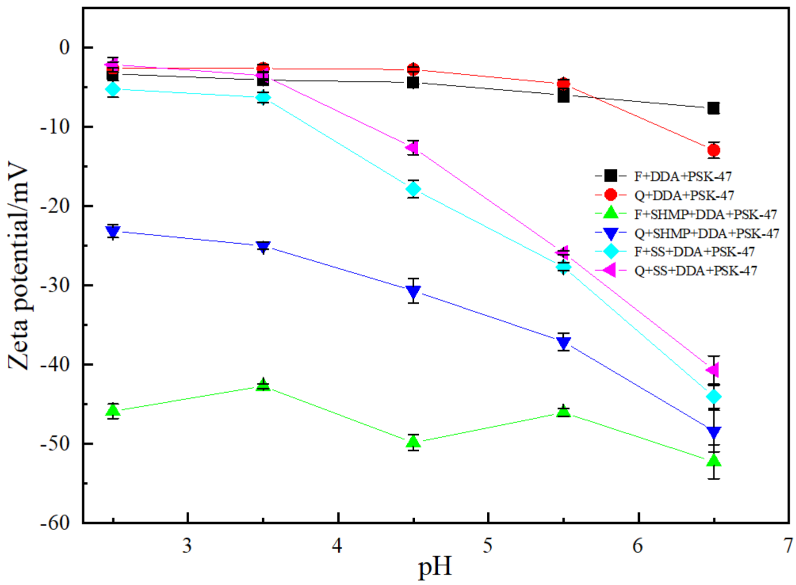

Fig. 9. Zeta potential of minerals as a function of pH value at three different solutions

3.3.3. FTIR studies

The analysis of the interaction between the surface of mineral and reagents were conducted to explore the mechanism by comparing the characteristic peaks before and after the interaction on the mineral. The IR spectra of the reagents, and the quartz and feldspar minerals are depicted in Fig. 10, respectively.

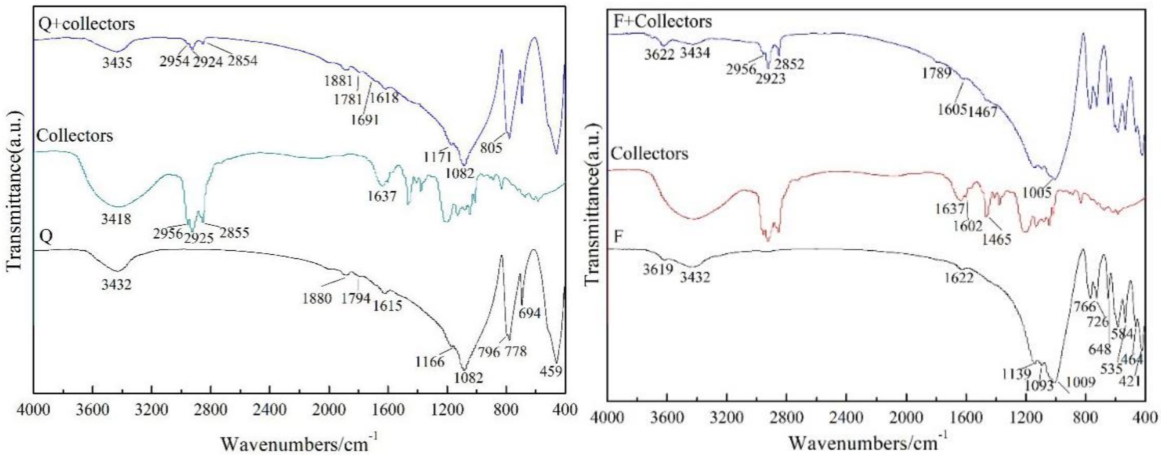

Fig. 10. The IR spectra of the interaction between quartz, feldspar, and the collector

The characteristic bands of alkyl chain between region 3000-2800 cm^{-1} at around 2956 cm^{-1}, 2925 and 2855 cm^{-1} are attributed to -CH3 asymmetric, -CH2 asymmetric and -CH2 symmetric stretching, respectively (Huo and Okuno., 1985). The intensity of the alkyl groups absorption bands increased significantly higher for feldspar compared to quartz, emphasizing more collectors be adsorbed on feldspar, the mixed collectors have only a weak physical effect on the surface of quartz. A broad peak between 3200 and 3700 cm^{-1} is due to O–H stretching (Kumar et al., 2015), the band at around 3619 cm^{-1} slightly shifted and the intensity also increased, moreover, the adsorption band at 1622 cm^{-1} corresponded to the H–O–H bending vibration of water (Yusan et al., 2014), which occurred a red shift to 1605 cm^{-1} after collector interaction on the surface of feldspar. The results elucidate that the adsorption effect between the collectors and the feldspar minerals and can be interpreted as physical adsorption by hydrogen bonds (Fan et al., 2015, Scharge et al., 2008). The characteristic stretching vibration peak at 1009 cm^{-1} associated with the Si–O or Al–O functional groups generated a displacement of 4 cm^{-1}, indicating there were strong chemical bonding between the Al-O sites of feldspar and characteristic groups of the mixed collector molecule. The chemisorption is stronger and not easy to be destroyed.

Under the weak acidic conditions of pH 4.5, quartz and feldspar are both negatively charged and could adsorb the cationic collector DDA. Although the surface is generally negatively charged, due to the reversibility of dissociation, there are still positively charged regions, where the ion adsorption occurred, resulting from the electrostatic interaction between the positive sites on the minerals surface and the anionic charge of the collector. Furthermore, combined literature report (Ibrahim et al., 2014) and our infrared studies, it could be reasoned that the molecule adsorption appeared to be through hydrogen bonding involving the electronegative N atoms of the respective functional groups and the hydroxy groups, that is to say, amino are H-bonded to the negatively charged silanol.

In addition to above mentioned two adsorption ways, also chemisorption on the surface of feldspar, while the adsorption effect on the surface of quartz was only the weaker physical adsorption. Thus, it is worthwhile to note that the adsorption of collectors on the surface of feldspar was stronger than that of quartz, the cationic-anion surfactants have excellent selectivity for collecting feldspar.

To explore the mechanism of depressants any further, the IR spectra before and after the interaction was measured as shown in Fig. 11 and Fig. 12.

Obviously, the intensity of the alkyl groups absorption bands decreased in terms of quartz but not significantly in feldspar. It is based on the inhibition principle that the sodium hexametaphosphate has the desorption effect between collectors and quartz surface. however, the desorption for the feldspar is negligible. The peaks of O–H at around 3435 cm^{-1} shifted similarly in the cases of quartz and feldspar after adding sodium hexametaphosphate, which is considered as the adsorption on the surface of minerals.

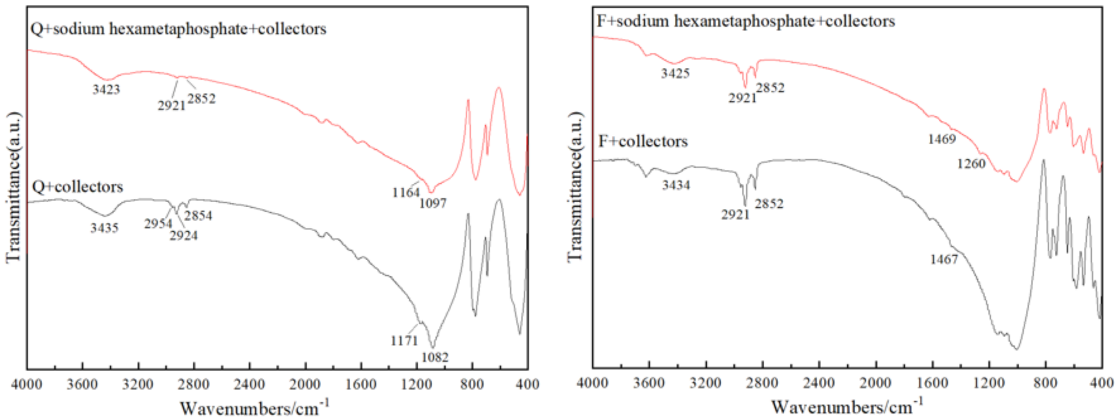

Fig. 11. The IR Spectra of the effect of sodium hexametaphosphate on quartz (a) and feldspar (b).

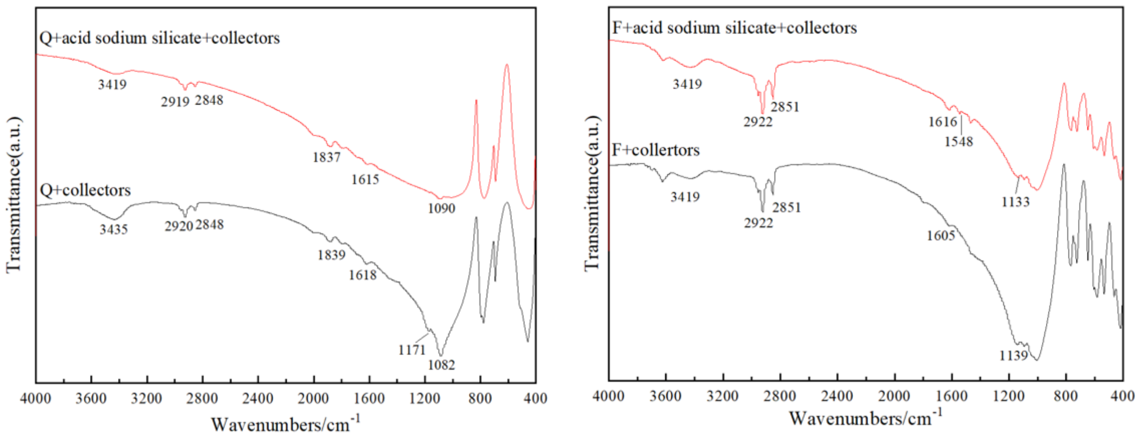

Fig. 12. The IR Spectra of the effect of acid sodium silicate on quartz (a) and feldspar (b)

From Fig. 12, the quartz and feldspar spectrums still display several obvious bands in the region 3000-2800 cm-1. The intensity of the alkyl groups slightly weakened in the quartz spectrum comparing with that of feldspar. Equally, the shifted peaks of O–H also are attributed to the adsorption on the surface of minerals.

3.3.4. Solution chemistry analysis of depressants

Based on the equal activities and equilibrium constants, the distribution coefficient of the dissociation conditions as a function of pH can be described Fig. 13.

Fig. 13 shows the $H_2PO_4^-$ has dominate position in hydrolytic components of sodium hexametaphosphate, H_2SiO_3 colloidal particles are the main existing form in acid sodium silicate under the condition of flotation test in which the pulp was subjected to pH 4.5.

The inhibition mechanism of sodium hexametaphosphate and acid sodium silicate can be summarized as follows: the former could desorb the weak adsorption collector on the surface of quartz just like the rinsing effect with deionized water. The active component of latter is H_2SiO_3 colloidal particles, which readily polymerize and adsorb on the siloxane tetrahedron groups of silicate minerals thus to retard the adsorption of collectors.

Combining solution chemistry, contact angle, Zeta, and infrared results, the addition of sodium hexametaphosphate has little effect on the contact angle of feldspar and quartz, while the addition of sodium silicate will decrease the contact angle of both feldspar and quartz. Secondly, adding the sodium hexametaphosphate and acid sodium silicate, feldspar exhibit more negative potential compared to the zeta potential of quartz at the same condition. Thirdly, in the infrared spectrum, the intensity of the alkyl groups absorption bands increased in terms of quartz but not significantly in feldspar after the addition of sodium hexametaphosphate, while the intensity of alkyl groups in the spectra of feldspar and quartz slightly weakened after the addition of sodium silicate. This indicates that sodium hexametaphosphate, without changing the adsorption of DDA+SPS agents on feldspar, resolved the agents on the surface of quartz and increased its surface potential. And sodium silicate not only prevents the adsorption of the collector on the surface of quartz, but also prevents the adsorption of the collector on the surface of feldspar.

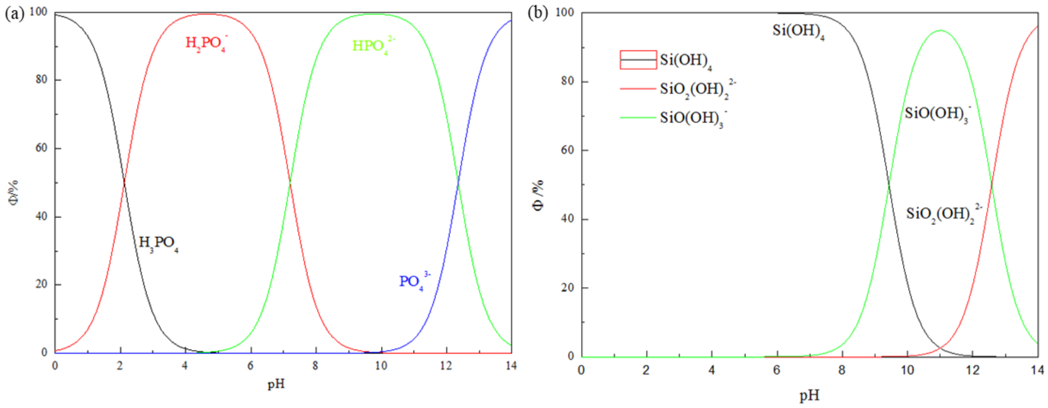

Fig. 13. The component distribution coefficient of sodium hexametaphosphate (a) and acid sodium silicate, (b) as a function of pH

4. Conclusions

The mixed collector DDA/sulfonate with the ratio of 1/3 preferentially floated feldspar. The Al_2O_3 content of the flotation concentrate was approximately 12%, when the concentrations of DDA and sulfonate were 40 mg/L and 120 mg/L, respectively. Sodium hexametaphosphate increased the grade of feldspar by 3% at a low concentration of 50 mg/L. Whereas, the inhibition ability of acid sodium silicate is poorer, and the consumption is 2-3 times higher than of that of sodium hexametaphosphate. Thus, sodium hexametaphosphate had better performance than acid sodium silicate for quartz-feldspar separation.

The presence of the mixed collector can increase the zeta potentials of quartz and feldspar because of the formation of positively charged complex. The charge difference caused by co-adsorption of sulfonate and DDA at pH 4.5 facilitates feldspar flotation, which could be further enlarged by sodium hexametaphosphate. The results elucidate that exhibiting potential difference is the key factor for the selected feldspar flotation.

The mixed collector caused a higher feldspar contact angle, and the hydrophobicity on the surface of feldspar became stronger. It is speculated that the action modes of two depressants caused different influence on the contact angle of quartz and feldspar. The electronic interactions, hydrogen bonding and chemical adsorption play an important role in the adsorption of collectors on the feldspar surface, whereas the adsorption form of collectors on the surface of quartz only is physical interactions. Therefore, the adsorption of collectors on the feldspar surface is stronger than quartz, the mixed collectors and sodium hexametaphosphate has high collecting and selectivity ability to feldspar.

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References

DING Z., LI J., YUAN J.Q., YU A.M., WEN S.M., BAI S.J., 2023. *Insights into the influence of calcium ions on the adsorption behavior of sodium oleate and its response to flotation of quartz: FT-IR, XPS and AMF studies.* Minerals Engineering, 204: 108437.

SHEN L F., SUN N., XU R., SUN W., WANG L., 2023. *Adsorption mechanisms of activated surface of quartz and feldspar with mixed NaOL/DDA.* Sep Purif Technol, 314: 123501.

ZHANG Y., HU Y.H., SUN N., LIU R.Q., WANG Z., WANG L., SUN W., 2018. *Systematic review of feldspar beneficiation and its comprehensive application*. Minerals Engineering, 128: 141-152.

MONTIEL-ANAYA J.A., FRANCO V., 2019. *FORC study of the ferromagnetic impurities in Na and K feldspars of "El Realejo" mine.* AIP Advances, 2019, 9(3): 35-38.

LIU H.G., LIN W.X., HONG M.H., 2021. *Hybrid laser precision engineering of transparent hard materials: challenges, solutions and applications.* Light: Science and Applications, 10(1): 162.

SUN N., WANG G.D., GE P., SUN W., XU L.H., TAGN H.H., WANG L., 2023. *Selective flotation of quartz from feldspar using hydroxypropyl starch as depressant.* Minerals Engineering, 195: 108022.

XU L., JIAO F., JIA W., PAN Z.C., HU C.Q., QIN W.Q., 2020. *Selective flotation separation of spodumene from feldspar using mixed anionic/nonionic collector.* Colloids & Surfaces A: Phys. Eng. Asp, 594: 124605.

LARSEN E, KLEIV R.A., 2016. *Flotation of quartz from quartz-feldspar mixtures by the HF method*. Minerals Engineering, 98: 49-51.

PERRY D.L., TSAO L, GAUGLER K.A., 1983. *Surface study of HF- and HF H2SO4-treated feldspar using Auger electron spectroscopy*. Geochimica et Cosmochimica Acta, 47(7): 1289–1291.

HEYES G.W., ALLAN G.C., BRUCKARD W.J., SPARROW, G.J., 2013. *Review of flotation of feldspar*. Mineral Processing and Extractive Metallurgy, 121(2): 72–78.

SHU K., XU L., WU H., TAGN Z., LUO L.P., YAGN J., XU Y.B., FENG B., 2020. *Selective flotation separation of spodumene from feldspar using sodium alginate as an organic depressant.* Sep Purif Technol, 248: 117122.

KOU J., XU S., SUN T., SUN C., GUO Y., WANG C., 2016. *A study of sodium oleate adsorption on Ca2+ activated quartz surface using quartz crystal microbalance with dissipation.* International Journal of Mineral Processing, 154: 24–34.

WEN C., HONG C.J., LUO L.Q., 2003. *Flotation Separation of Quartz from Feldspar under Hydrofluoric Acid-free and Less Sulfuric Acid Conditions*. Mining and Metallurgical Engineering, 23(3): 35-37.

LIU Y., ZHANG K., 1993. *Adsorption of sodium oleate and dodecyl amine hydrochloride on feldspar and quartz.* Mining and Metallurgical Engineering, 13(2): 27-30.

BAI J.M., FAN W.Y., NAN G.Z., LI S.P., YU B.S., 2010. *Influence of Interaction Between Heavy Oil Components and Petroleum Sulfonate on the Oil–Water Interfacial Tension.* Journal of Dispersion Science & Technology, 31(4): 551-556.

ZHU H.L., DENG H.B., CHEN C., 2015. *Flotation separation of andalusite from quartz using sodium petroleum sulfonate as collector.* Transactions of Nonferrous Metals Society of China, 25(4): 1279-1285.

FENG Q., WEN S., ZHAO W., CHEN Y., 2018. *Effect of calcium ions on adsorption of sodium oleate onto cassiterite and quartz surfaces and implications for their flotation separation.* Sep Purif Technol, 200: 300–306.

LIU C.F., MIN F.F., LIU L.Y., CHENG J., DU J., 2018. *Mechanism of hydrolysable metal ions effect on the zeta potential of fine quartz particles.* Journal of Dispersion Science and Technology, 39 (2), 298–304.

WANG J.Y., XIE L., LU Q.Y., WANG X.G., WANG J.M., ZENG H.B., 2020. *Electrochemical investigation of the interactions of organic and inorganic depressants on basal and edge planes of molybdenite.* Journal of colloid and interface science, 570: 350–361.

CHEN Z.J., REN Z.J., GAO H.M., ZHENG R.J., JIN Y.L., NIU G.G., 2019. *Flotation studies of fluorite and barite with sodium petroleum sulfonate and sodium hexametaphosphate.* Journal of Materials Research and Technology, 8 (1), 1267–1273.

RAMIREZ A., ROJAS A., GUTIERREZ L., LASKOWSKI, J.S., 2018. *Sodium hexametaphosphate and sodium silicate as dispersants to reduce the negative effect of kaolinite on the flotation of chalcopyrite in seawater.* Minerals Engineering, 125: 10–14.

GAN W., CROZIER B., LIU Q., 2009. *Effect of citric acid on inhibiting hexadecane–quartz coagulation in aqueous solutions containing Ca2+, Mg2+ and Fe3+ ions.* International Journal of Mineral Processing, 92 (1–2): 84–91.

MYERS D., 1999. *Surfaces, interfaces, and colloids - principles and applications*. New Yorks: JohnWiley&Sons, Inc, 415-447.

KANGAL O., BULUT G., YEŞILYURT Z, GUVEN, O., BURAT, F., 2017. *An Alternative Source for Ceramics and Glass Raw Materials: Augen-Gneiss.* Minerals, 7(5): 70.

TSUYOSHI H., YUKI A., MOHSEN F., NAOKO O., KEIKO S., TAKEHIKO T., KATSUMI D., 2011. *Effect of microorganisms on flocculation of quartz*. International Journal of Mineral Processing, 102: 107-111.

ABA KA-WOOD G., ADDAI-MENSAH J., SKINNER W., 2016. *Physicochemical Characterization of Monazite, Hematite and Quartz Minerals for Flotation.* 4th Ummat Biennial International Mining and Mineral Conference.

Kursun I., 2010. *Determination of flocculation and adsorption desorption characteristics of Na-feldspar concentrate in the presence of different polymers,* Physicochemical Problems of Mineral Processing, 23: 127-142.

LIU J., CHEN W.Y., HAN Y.X., YUAN H.Q., 2010. *Study on Flotation Mechanism of Separation of Potassium Feldspar from Quartz with Anion and Cation Mixed Collector.* Advanced Materials Research, 826: 106-113.

PANANDIKER R.K., SMITH S.D., MCCHAIN R.J., BARRERA, C.A., 2015. *Branched blocky cationic organopolysiloxane.*

LU R.C., CAO A.N., LAI L.H., ZHU, B.Y., ZHAO, G.X., XIAO J.X., 2007. *Interaction between bovine serum albumin and equimolarly mixed cationic-anionic surfactants decyltriethylammonium bromide-sodium decyl sulfonate.* Colloids Surf B Bio interfaces, 54(1): 20-24.

VIDYADHAR A., RAO K.H., 2007. *Adsorption mechanism of mixed cationic/anionic collectors in feldspar-quartz flotation system.* Journal of Colloid and Interface Science, 2007, 306(2): 195-204.

HUO P.P., OKUNO I., 1985. *Alkyl Chain Length and the Spectral Characteristics of p-Aminophenones.* Applied Spectroscopy, 39(2): 339-342.

KUMAR B., SMITA K., CUMBAL L., ANGULO Y., 2015. *Fabrication of silver nanoplates using Nephelium lappaceum (Rambutan) peel: A sustainable approach*. Journal of Molecular Liquids, 211: 476-480.

YUSAN S, KORZHYNBAYEVA K, AYTAS S., 2014. *Preparation and investigation of structural properties of magnetic diatomite nanocomposites formed with different iron content.* Journal of Alloys & Compounds, 608: 8-13.

FAN C.H., ZHANG Y.C., WANG J.H., 2013. *Study on the Co-Adsorption Mechanism of Pb and Chlorpyrifos on Arid Loess in Northwestern China*. Spectroscopy & Spectral Analysis, 33(8): 2137-2142.

SCHARGE T., WASSERMANN T.N., SUHM M.A., 2008. *Weak Hydrogen Bonds Make a Difference: Dimers of Jet-Cooled Halogenated Ethanols*. International Journal of Research in Physical Chemistry & Chemical Physics, 222(8-9): 1407-1452.

IBRAHIM I, HUSSIN H, AZIZLI K., 2014. *A study on the interaction of feldspar and quartz with mixed anionic/cationic collector*. Malaysian Journal of Fundamental and Applied Sciences, 7(2): 101-107.