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## Effects of $\text{Ca}^{2+}$ and $\text{SO}_4^{2-}$ ions on fluorite flotation

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**Abstract:** The effects of  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  on the flotation behaviour of fluorite with sodium oleate as a collector and the underlying mechanism by which these effects were investigated via micro-flotation experiments, solution chemistry calculations, and X-ray photoelectron spectroscopy. The results indicated that the addition of  $\text{SO}_4^{2-}$  and  $\text{Ca}^{2+}$  inhibited fluorite flotation and the inhibition effect was increased by the addition of pH. This was mainly due to the increase of the sulphate-containing components in the solution and the adsorption of  $\text{SO}_4^{2-}$  on the surface of fluorite. With the increase of pH, the alkalinity of the solution increases,  $\text{OH}^-$  and more  $\text{SO}_4^{2-}$  are further adsorbed on the fluorite surface, thereby reducing the recovery of fluorite flotation.

**Keywords:** fluorite, flotation, calcium cation, sulphate anion

### 1. Introduction

Fluorite ( $\text{CaF}_2$ ), a widely distributed mineral, is an important and strategic non-renewable mineral (Foucaud et al., 2018; Tian et al., 2019; Liu et al., 2019). It contains 51.33% calcium and 48.67% fluorine (Zheng et al., 2018). Fluorite is extensively used in various fields such as metallurgy (Zhu et al., 2018), materials science (Chen et al., 2019), pesticides (Liu et al., 2019), and different chemical products (Yang et al., 2020; Jong et al., 2020).

As reserves of high-grade and easily sorted fluorite resources, the development of various resources associated with fluorite such as calcite-type fluorite mine, polymetallic fluorite mine, and barite–fluorite mine has intensified in recent years (Fa et al., 2006). The separation of fluorite and barite ( $\text{BaSO}_4$ ) has always been a difficult task in fluorite beneficiation (Lewandowski et al., 2019; Wang et al., 2020) because both of them have a similar floatability (Tasker, 1980; Marinakis and Shergold, 1985; Liu et al., 2020).

Flotation is the most commonly adopted beneficiation technique for separating fluorite from other gangue minerals (Feng et al., 2015; Foucaud et al., 2018). Flotation can be affected by numerous factors (Marinakis and Shergold, 1985; Filippova et al., 2018) such as pH, various ions in the pulp, and collectors (Sayilgan and Arol, 2004; Chennakesavulu et al., 2008). Conventional collectors such as fatty acids and their salts (Hu and Xu, 2003; Chen et al., 2018; Mielczarski et al., 2020) especially oleic acid and sodium oleate (NaOL) (Li et al., 2017; Foucaud et al., 2019; Mielczarski et al., 2020) are the most typically utilized collectors in fluorite flotation (Fa et al., 2006; Filippova et al., 2018; Filippov et al., 2019). Given that fluorite and barite have a similar floatability, some inhibitors are often added during flotation separation such as inhibitors of mixed aluminium sulphate, sodium hydroxide, and tannin extraction, as well as inhibitors of mixed sodium sulphate, sodium hydroxide, and starch, to separate fluorite from barite (Chen et al., 2017; Zhang et al., 2019; Tian et al., 2019).

$\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  are present in solution owing to mineral dissolution (fluorite and barite) and addition of sulphate inhibitors (Flores-Álvarez et al., 2017; Elizondo-Álvarez et al., 2017). Previous studies only have focused on the effects of a single ion such as  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ , and  $\text{F}^-$  on minerals (Free and Miller 1996; Sis and Chander, 2003; Filippova et al., 2014; Alroudhan et al., 2016; Filippov et al., 2019). Other studies reported that  $\text{CaOH}^+$  and  $\text{Ca}(\text{OH})_2$  are formed under the alkaline condition of  $\text{Ca}^+$ , which

affects the recovery of fluorite (Chen et al., 2017; Feng et al., 2018; Zhou et al., 2020). However, the effects of the combination of  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  on fluorite flotation have been rarely investigated. This study aimed to evaluate the effects of the addition of  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  on fluorite flotation. The function was observed via micro-flotation experiments, solution chemistry calculations, and X-ray photoelectron spectroscopy (XPS).

## 2. Materials and methods

### 2.1. Materials

A single fluorite sample was obtained from Guiyang, Guizhou Province, China. After handpicking, parts of the solid particles were crushed and then ground using a ceramic ball mill. The products were then dry-screened to obtain fractions 106  $\mu\text{m}$  in size for the micro-flotation experiments. The results of X-ray diffraction of fluorite are given in Fig. 1. Chemical analysis revealed that the fluorite sample contained 99.92%  $\text{CaF}_2$ .

Chemically pure sodium oleate (NaOL), which was used as a collector in this study, was bought from Shanghai Baisaiqin Chemical Technology Co., Ltd. (Shanghai, China). Anhydrous sodium sulphate ( $\text{Na}_2\text{SO}_4$ ) was procured from Hunan Zhuzhou Institute of Chemical Industry (Hunan, China). Anhydrous calcium chloride ( $\text{CaCl}_2$ ) was purchased from China Pharmaceutical Group Chemical Reagents Co., Ltd. (Beijing, China). Hydrochloric acid (HCl) and sodium hydroxide (NaOH), which were used as pH regulators, were acquired from Sinopharm Chemical Reagent Co., Ltd. (Beijing, China). Other reagents were of analytic grade, and deionized (DI) water (Pure water machine is purchased from Shanghai Hetai Instrument Co., Ltd., model Smart-S15UVF, resistivity 18.2  $\text{M}\Omega\cdot\text{cm}$  @25  $^\circ\text{C}$ ) was used in all experiments.

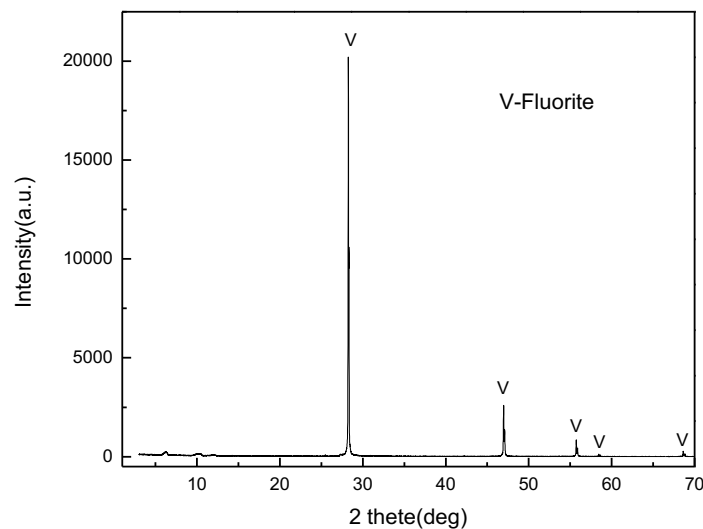


Fig. 1. XRD pattern of fluorite

### 2.2. Methods

#### 2.2.1. Solution chemistry calculation

Visual MINTEQ (Gustafsson, 2000) is a free chemical equilibrium model for calculating metal speciation, solubility equilibrium, and sorption for natural waters (Chávez and Miguel, 1976). This model combines state-of-the-art descriptions of sorption and complexation reactions. In this study, the ionic component of saturated fluorite dissolved in pure water, the pH of the solution, and ion activity under variable pH conditions were calculated using this software.

#### 2.2.2. Micro-flotation experiments

Micro-flotation experiments were performed in an XFGC II mechanical agitation flotation machine, Jilin Exploration Machinery Plant (Changchun, China). The impeller rotation speed was set at 1992 r/min.

For each experiments, 2.0 g of pure mineral sample was added into a 40 cm<sup>3</sup> flotation cell with 35 cm<sup>3</sup> deionized (DI) water. After conditioning for 1 min, 10<sup>-2</sup> mol/dm<sup>3</sup> CaCl<sub>2</sub> and Na<sub>2</sub>SO<sub>4</sub> solution were added successively. The slurry was then adjusted to the desired pH value by using NaOH or HCl for 1 min. The order by which the reagents were added and the conditioning time allotted were as follows: The ions were modified for 3 min and the collector for 2 min. Flotation was conducted for 3 min. The flotation products (both the concentrates and tailings) were collected, filtered, dried, and weighed to calculate mineral recoveries.

### 2.2.3. Surface analysis

The adsorption of SO<sub>4</sub><sup>2-</sup> on fluorite surfaces at pH 10 after the addition of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> was detected via XPS (Zhang et al., 2019). The measurements were performed using a K-ALPHA X-ray photoelectron spectrometer (Thermo Fisher Scientific Inc., USA). For each measurement, 2 g of a mineral sample was prepared each time to prepare the slurry according to the corresponding ions and pH conditions. The slurry was centrifuged (GL-20G-II) at 9000 r/min for 20 min to separate solid and liquid minerals. The solid minerals were washed with distilled water twice and then dried in a vacuum oven at below 25°C (Xu, et al., 2020).

## 3. Results and discussion

### 3.2. Micro-flotation experiments

Fluorite recovery initially increased and then tended to stabilize as collector dosage increased (Fig. 2[a]). The highest fluorite recovery was obtained when the collector concentration was 5×10<sup>-5</sup> mol/dm<sup>3</sup> (Chen et al., 2017). The addition of chlorine ion and sodium ion did not change the recovery of fluorite flotation whereas the addition of Ca<sup>2+</sup> had an inhibitory effect on fluorite mainly because the reaction of calcium ion with the collector sodium oleate would form calcium oleate precipitates (Marinakos and Shergold, 1985; Filippova et al., 2014); hence, reducing collector concentration. The addition of SO<sub>4</sub><sup>2-</sup> can also reduce fluorite flotation recovery. However, its recovery was still higher than when Ca<sup>2+</sup> was added primarily because SO<sub>4</sub><sup>2-</sup> easily adsorbs on the surface of fluorite and forms calcium sulphate precipitates, thereby inhibiting the collection of fluorite by sodium oleate (Zhang et al., 2019). Meanwhile, SO<sub>4</sub><sup>2-</sup> can promote fluorite dissolution and consume the collector by dissolved Ca<sup>2+</sup>. Compared with the absence of ions, the addition of combined ions substantially reduced fluorite flotation recovery (Fig. 2[b]) probably because of the synergistic inhibition of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>.

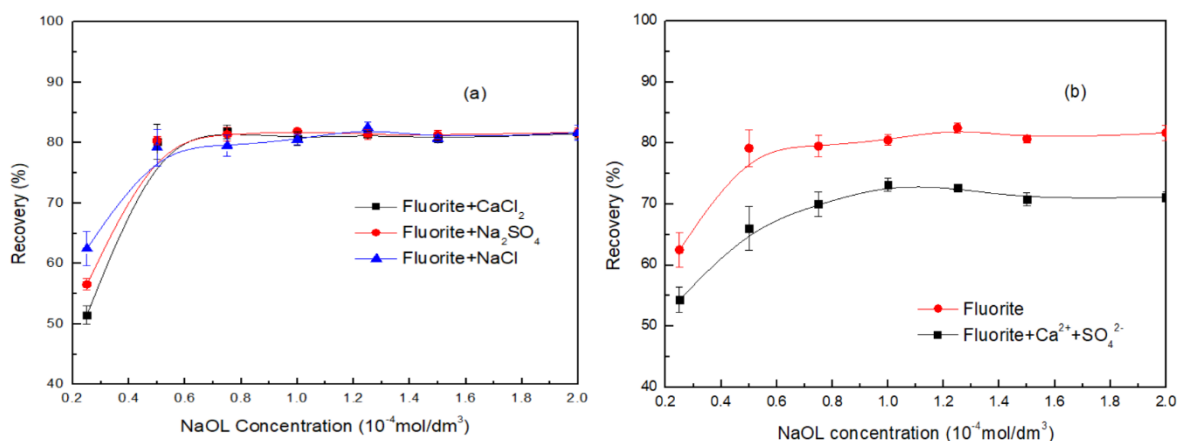


Fig. 2. Recovery of fluorite as a function of NaOL dosage  $C_{(ions)} = 1 \times 10^{-2}$  mol/dm<sup>3</sup>, pH 6.8

Furthermore, the effects of different ions on fluorite flotation under different pH conditions were investigated via micro-flotation experiments. In the absence of the ions, fluorite recovery decreased from 84% to 71.47% at pH 8.5–10.5, indicating that fluorite floatability decreased as pH increased (Fig. 3). When Ca<sup>2+</sup> alone was added into the solution, fluorite recovery relatively decreased compared with that without ion addition. Compared with the ion-free condition, the addition of SO<sub>4</sub><sup>2-</sup> almost did not

affect fluorite flotation. When  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  were added, fluorite recovery sharply decreased as pH increased. Thus, under strongly alkaline conditions, the addition of  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  exerted a strong inhibitory effect on fluorite flotation.

Moreover, the effects of ion concentrations on flotation recovery under different pH conditions were examined (Fig. 4). The ions had negligible effects on fluorite flotation as ion concentrations increased at pH 6.8. At pH 9.0, fluorite recovery decreased as ion concentrations further increased. These results indicated that increases in ion concentrations had a considerable effect on fluorite recovery under alkaline conditions.

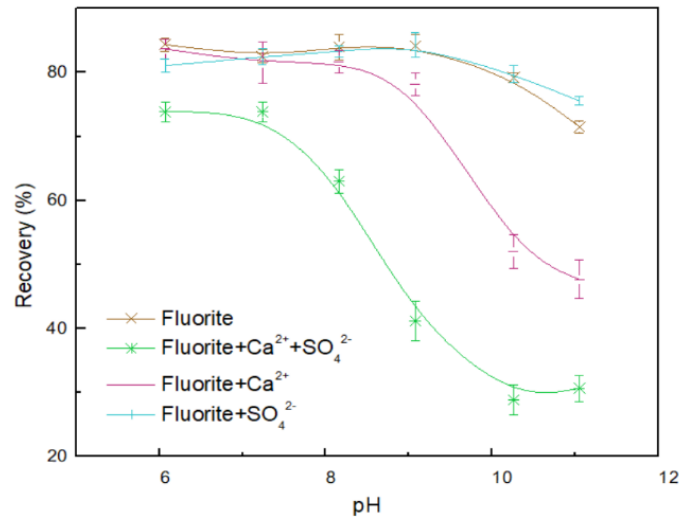


Fig. 3. Recovery of fluorite as a function of pH.  $C_{(\text{ions})} = 1 \cdot 10^{-2} \text{ mol/dm}^3$ ,  $C_{(\text{NaOL})} = 5 \cdot 10^{-5} \text{ mol/dm}^3$

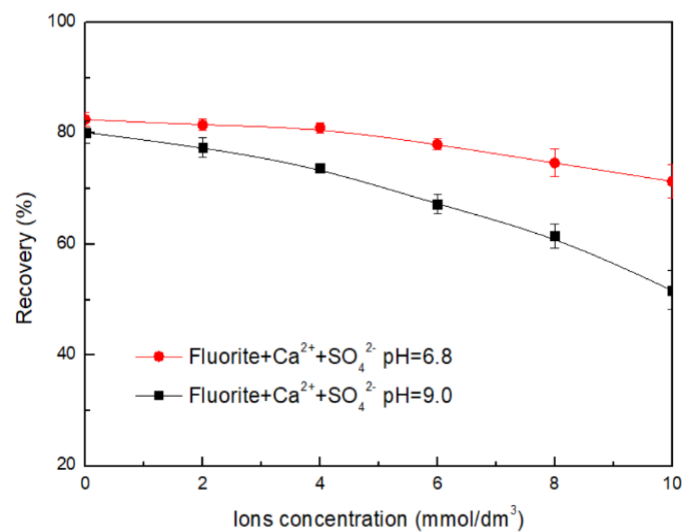
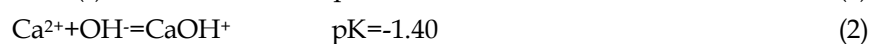
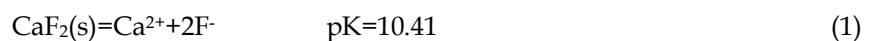
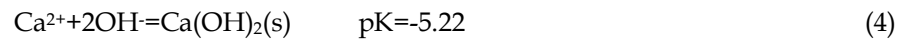
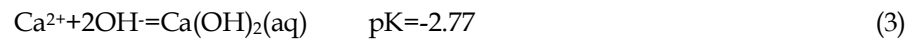


Fig. 4. Recovery of fluorite in different pH as a function of ion concentration.  $C_{(\text{NaOL})} = 5 \cdot 10^{-5} \text{ mol/dm}^3$

### 3.3. Solution chemical calculation

In flotation solutions, interactions between collectors and fluorite are mainly influenced by charges on mineral surfaces, electrical properties, pH, temperatures, the metal ions added, and ionic strengths. However, these factors are closely related to water chemistry in the flotation process (Sayilgan and Arol, 2004; Foucaud et al., 2018). According to previous studies, the chemical reactions and equilibrium constants of fluorite in an aqueous solution are as follows (Free and Miller 1996):





Changes in various components in the solution under different pH conditions were monitored via solution chemical calculations using Visual MINTEQ 3.0 (Xu et al., 2020). Among these components, Sat index can determine the presence of precipitation in the solution. A Sat index greater than 0 indicates the presence of precipitation, whereas a Sat index less than 0 denotes the absence of precipitation. Herein, the temperature was set at 25°C.

Changes in solution saturation index under different pH and ion conditions are exhibited in Fig. 6. Variations in the concentration of each component in the solution under different pH and ion conditions are shown in Fig. 5. When no ions were added, the concentration of  $\text{Ca}^{2+}$ ,  $\text{F}^-$ , and  $\text{CaF}^+$  remained the same within the pH range of 2-12. Moreover,  $\text{CaOH}^+$  concentration increased but  $\text{HF}$  and  $\text{HF}_2^-$  concentration decreased as pH increased (Fig. 5[a]). When adding  $\text{SO}_4^{2-}$  and  $\text{Ca}^{2+}$ , the solution added sulphate-containing components ( $\text{CaSO}_4(\text{aq})$ ,  $\text{SO}_4^{2-}$ ,  $\text{HSO}_4^-$ ), the calcium components ( $\text{Ca}^{2+}$ ,  $\text{CaF}^+$ ,  $\text{CaOH}^+$ ) increased, while fluoride composition ( $\text{F}^-$ ,  $\text{HF}(\text{aq})$ ,  $\text{HF}_2^-$ ) decreased slightly (Fig. 5 [d]). As the pH (from 2 to 12) increases, the concentration of  $\text{CaOH}^+$  increases, while the concentration of  $\text{HSO}_4^-$ ,  $\text{HF}(\text{aq})$  and  $\text{HF}_2^-$  decreases, moreover the concentration of the remaining components remains unchanged (Wang and Hu, 1988).

The saturation index was less than 0, indicating that no precipitation formed in the solution. The

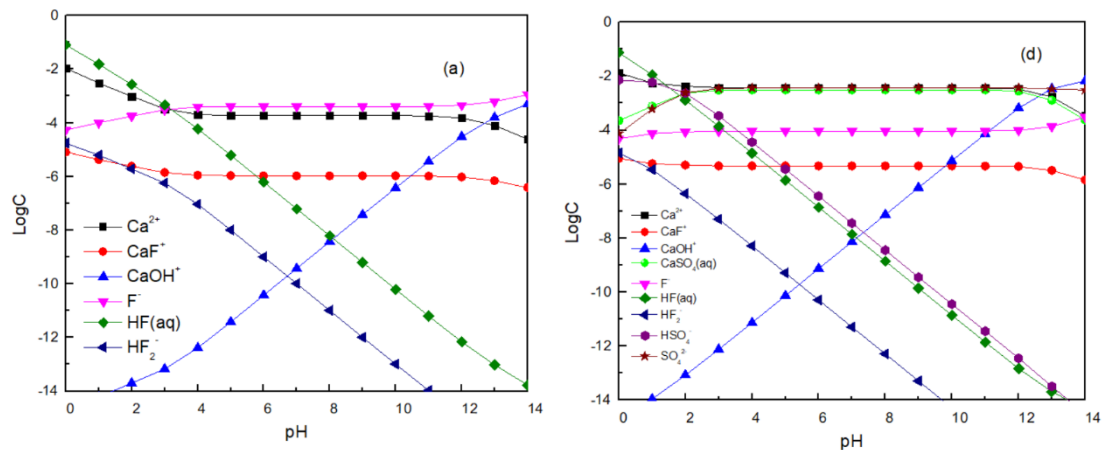


Fig. 5. Ions activity of (a) purity fluorite, and (d) fluorite with combined ion as a function of pH.  $C_{(\text{ions})} = 1 \times 10^{-2}$  mol/dm<sup>3</sup>

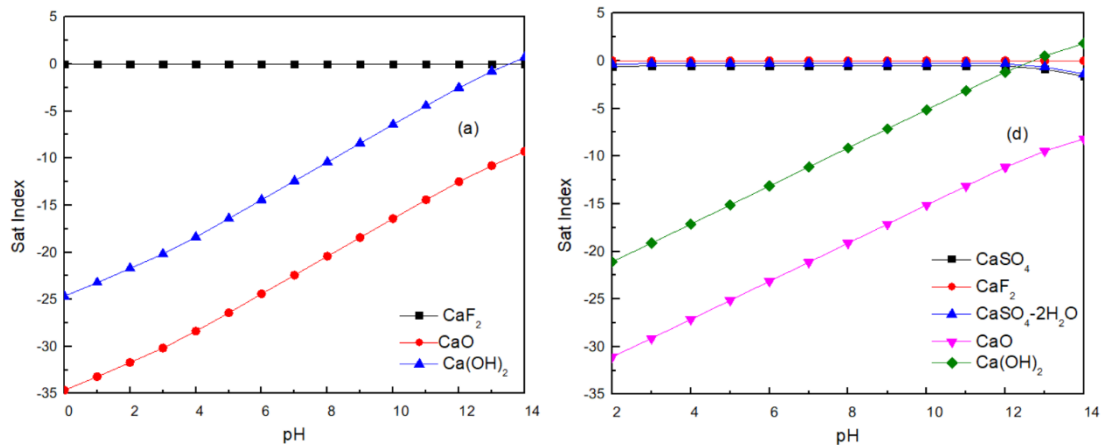


Fig. 6. Sat Index (a) purity fluorite, (b) fluorite with  $\text{Ca}^{2+}$ , (c) fluorite with  $\text{SO}_4^{2-}$  and (d) fluorite with combined ion added as a function of pH.  $C_{(\text{ions})} = 1 \times 10^{-2}$  mol/dm<sup>3</sup>

CaF<sub>2</sub> saturation index remained the same within the range of pH from 2 to 12 (Fig. 6[a]). When the sulphate-containing components were added to the solution, and then the saturation index of Ca(OH)<sub>2</sub> and CaO increased significantly. The saturation index of CaSO<sub>4</sub> and CaSO<sub>4</sub>•2H<sub>2</sub>O tended toward 0, indicating the presence of large amounts of CaSO<sub>4</sub>(aq) (Azimi et al., 2008) in the solution after the addition of the combined ions. With the increase of pH (from 2 to 12), the saturation index of Ca(OH)<sub>2</sub> and CaO showed an increasing trend. (Fig. 6[d]).

In summary, solution chemical calculations revealed that sulphate-containing components were added in the solution, the concentration of calcium components (Ca<sup>2+</sup>, CaF<sup>-</sup>, CaOH<sup>+</sup>), especially the saturation indexes of CaSO<sub>4</sub> and CaSO<sub>4</sub>•2H<sub>2</sub>O approached to 0, when Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> were added. As the pH increases (from 2 to 12), the concentration of CaOH<sup>+</sup>, Ca(OH)<sub>2</sub>, and CaO in the solution increases.

### 3.4. Surface analysis

The surface of fluorite after pre-treatment with 10<sup>-2</sup> mol/dm<sup>3</sup> of the ions at pH 6.8 and 10 was examined via XPS (Table 2 and Fig. 7). No sulphur atoms were found on the fluorite surface at pH 6.8 in the absence of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>. After conditioning in the presence of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>, the content of Ca and F on the surface of fluorite decreased by 1.4% and 4.95%, while the content of S and O on the surface of fluorite increased by 1.07% and 2.97%, indicating that SO<sub>4</sub><sup>2-</sup> were adsorbed on fluorite surface. When the pH was 10, S on the surface of fluorite increased by 0.38%, while O increased by 1.14%, while the content of fluorine and calcium remained unchanged, which indicated that more SO<sub>4</sub><sup>2-</sup> was adsorbed on the surface of fluorite. The high-resolution spectra of Ca 2P, S 2P, and O 1S are shown in Fig. 7, in the absence of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>, the peak of S cannot be detected on the surface of fluorite at pH 6.8. The binding energies of Ca 2p 2/3 and Ca 2p 1/2 are 347.95 and 351.47 eV, respectively, and the binding energies of O 1s are 531.19 and 532.79 eV, respectively. In the presence of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>, when the pH is 6.8, the Ca2p 2/3 signal shifts by 0.5 eV, while the Ca 2p 1/2 signal shifts by 0.52 eV, the O 1s signal shifts by 0.7 and 1 eV (Gao et al., 2019; Tian et al., 2019). Figure 7(e) indicated that S 2p<sub>3/2</sub> electrons were acquired, the binding energy of S 2p<sub>3/2</sub>. It is 169.66eV because of the adsorption of SO<sub>4</sub><sup>2-</sup> on the surface of fluorite (Cui et al., 2020; Wang et al., 2020). When the pH increased to 10, the Ca 2P 2/3, Ca 2P 1/2, and S 2p<sub>3/2</sub> signals were basically unshifted, and the O 1s signal offset by 0.11 and 1.43eV, respectively, a new peak-to-peak value of 531.31 eV is formed (detected and assigned to Ca(OH)<sub>2</sub>) (Vincent, 1999).

Table 2. Concentration (at. %) of elements measured by XPS on the surfaces of fluorite under different reagent conditions C<sub>(ions)</sub>=1 × 10<sup>-2</sup> mol/dm<sup>3</sup>

Reagent conditions	Element analyzed			
	Ca	S	F	O
pH 6.8 Fluorite	34.07	-	48.01	3.96
Fluorite + CaCl <sub>2</sub> + Na <sub>2</sub> SO <sub>4</sub> , pH 6.8	32.47	1.07	43.06	6.94
Fluorite + CaCl <sub>2</sub> + Na <sub>2</sub> SO <sub>4</sub> , pH 10	32.34	1.45	43.28	8.08

### 4. Conclusions

Under laboratory-scale conditions, the effect of the addition of combined ions under different pH conditions on fluorite flotation was investigated, and reached the following conclusions:

1. After the addition of the ions, the concentration of the calcium-containing components in the solution increases, furthermore the addition of sulphate-containing component, especially the concentrations of CaSO<sub>4</sub> and CaSO<sub>4</sub>•2H<sub>2</sub>O.
2. The addition of combined ions has an inhibitory effect on the flotation of fluorite, mainly due to the increase of sulphate-containing components in the solution and the adsorption of SO<sub>4</sub><sup>2-</sup> on the surface of fluorite.
3. Under the conditions of the same ion, the content of Ca(OH)<sub>2</sub>, CaOH<sup>+</sup> and CaO in the solution increased with the increase of pH.
4. The flotation recovery of fluorite decreased significantly with the increase of pH, the main reason is the further adsorption of OH<sup>-</sup> and SO<sub>4</sub><sup>2-</sup>.

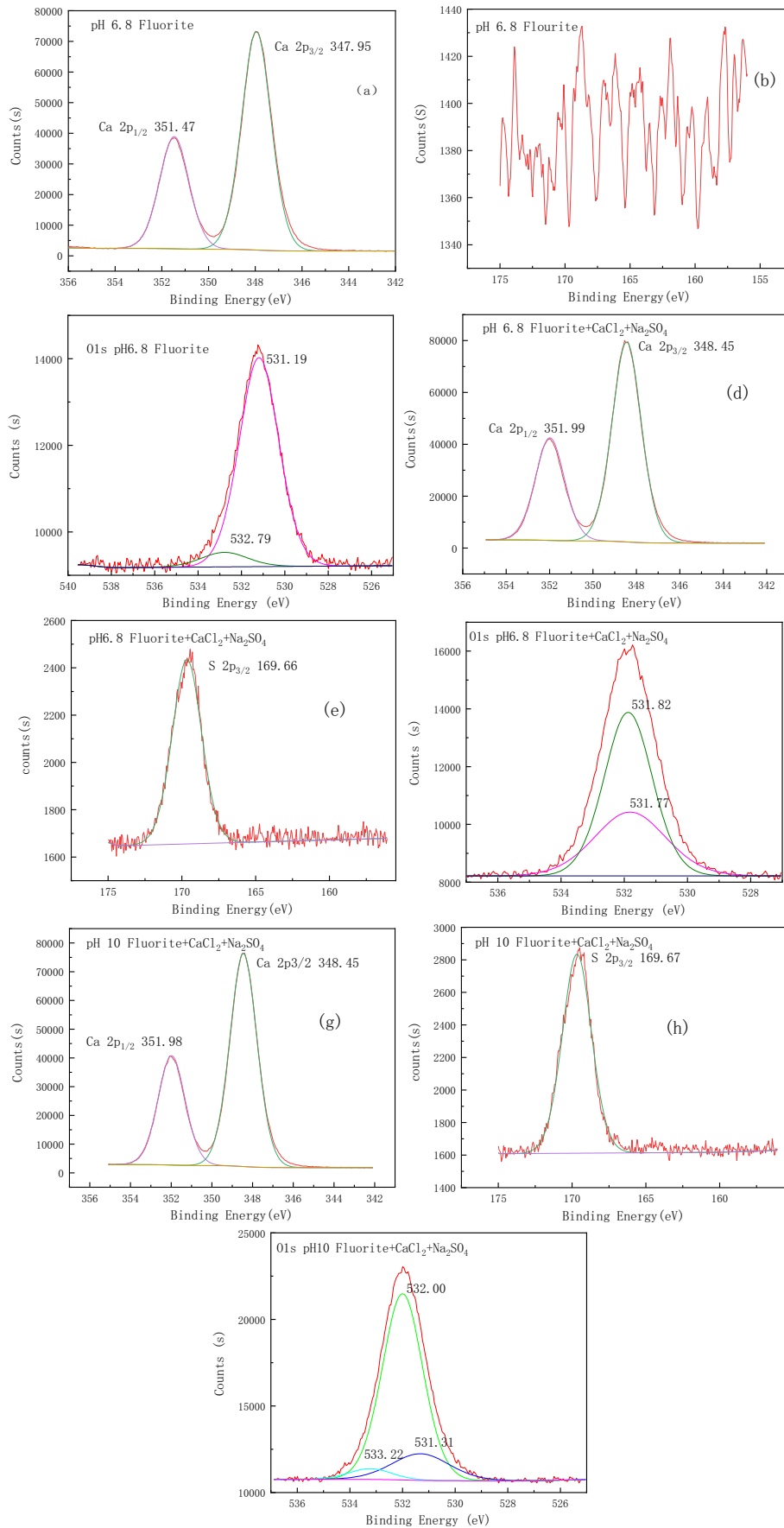


Fig. 7. XPS spectra of Ca 2P, S 2P, O 1S regions for fluorite (a), (b), and (c) fluorite + Ca<sup>2+</sup> + SO<sub>4</sub><sup>2-</sup> at pH 6.8 (d), (e) and (f) fluorite + Ca<sup>2+</sup> + SO<sub>4</sub><sup>2-</sup> at pH 10 (g), (h), and (i)

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## References

- ALROUDHAN, A., VINOGRADOV, J. and JACKSON, M.D., 2016. *Zeta potential of intact natural limestone: Impact of potential-determining ions Ca, Mg and SO<sub>4</sub>*. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 493, 83-98.
- AZIMI, G., PAPANGELAKIS, V.G. and DUTRIZAC, J.E., 2008. *Development of an MSE-based chemical model for the solubility of calcium sulphate in mixed chloride-sulphate solutions*. *Fluid Phase Equilibria*. 266, 172-186.
- CHEN, W., FENG, Q., ZHANG, G., LIU, D. and LI, L., 2018. *Selective flotation of scheelite from calcite using calcium lignosulphonate as depressant*. *Minerals Engineering*. 119, 73-75.
- CHEN, W., FENG, Q., ZHANG, G., YANG, Q. and ZHANG, C., 2017. *The effect of sodium alginate on the flotation separation of scheelite from calcite and fluorite*. *Minerals Engineering*. 113, 1-7.
- CHEN, W., FENG, Q., ZHANG, G., YANG, Q., ZHANG, C. and XU, F., 2017. *The flotation separation of scheelite from calcite and fluorite using dextran sulfate sodium as depressant*. *International Journal of Mineral Processing*. 169, 53-59.
- CHEN, Z., REN, Z., GAO, H., ZHENG, R., JIN, Y. and NIU, C., 2019. *Flotation studies of fluorite and barite with sodium petroleum sulfonate and sodium hexametaphosphate*. *Journal of Materials Research and Technology*. 8, 1267-1273.
- CHENNAKESAVULU, K., RAJU, G.B., PRABHAKAR, S., NAIR, C.M. and MURTHY, K.V.G.K., 2008. *Adsorption of oleate species at the fluorite-aqueous solution interface*. *Int. J. Miner. Process.* 90, 101-104.
- CUI, Y., JIAO, F., WEI, Q., WANG, X. and DONG, L., 2020. *Flotation separation of fluorite from calcite using sulfonated lignite as depressant*. *Separation and Purification Technology*. 242,
- ELIZONDO-ÁLVAREZ, M.A., FLORES-ÁLVAREZ, J.M., DÁVILA-PULIDO, G.I. and URIBE-SALAS, A., 2017. *Interaction mechanism between galena and calcium and sulfate ions*. *Minerals Engineering*. 111, 116-123.
- FA, K., NGUYEN, A.V. and MILLER, J.D., 2006. *Interaction of calcium dioleate collector colloids with calcite and fluorite surfaces as revealed by AFM force measurements and molecular dynamics simulation*. *International Journal of Mineral Processing*. 81, 166-177.
- FENG, B., LUO, X., WANG, J. and WANG, P., 2015. *The flotation separation of scheelite from calcite using acidified sodium silicate as depressant*. *Minerals Engineering*. 80, 45-49.
- FENG, Q., WEN, S., ZHAO, W. and CHEN, Y., 2018. *Effect of calcium ions on adsorption of sodium oleate onto cassiterite and quartz surfaces and implications for their flotation separation*. *Separation and Purification Technology*. 200, 300-306.
- FILIPPOV, L.O., FILIPPOVA, I.V., LAFHAJ, Z. and FORNASIERO, D., 2019. *The role of a fatty alcohol in improving calcium minerals flotation with oleate*. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 560, 410-417.
- FILIPPOVA, I.V., FILIPPOV, L.O., DUVERGER, A. and SEVEROV, V.V., 2014. *Synergetic effect of a mixture of anionic and nonionic reagents: Ca mineral contrast separation by flotation at neutral pH*. *Minerals Engineering*. 66-68, 135-144.
- FILIPPOVA, I.V., FILIPPOV, L.O., LAFHAJ, Z., BARRES, O. and FORNASIERO, D., 2018. *Effect of calcium minerals reactivity on fatty acids adsorption and flotation*. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 545, 157-166.
- FLORES-ÁLVAREZ, J.M., ELIZONDO-ÁLVAREZ, M.A., DÁVILA-PULIDO, G.I., GUERRERO-FLORES, A.D. and URIBE-SALAS, A., 2017. *Electrochemical behavior of galena in the presence of calcium and sulfate ions*. *Minerals Engineering*. 111, 158-166.
- FOUCAUD, Y., BADAWI, M., FILIPPOV, L.O., FILIPPOVA, I.V. and LEBEGUE, S., 2018. *Surface properties of fluorite in presence of water: An atomistic investigation*. *J. Phys. Chem. B*. 122, 6829-6836.
- FOUCAUD, Y., FILIPPOVA, I.V. and FILIPPOV, L.O., 2019. *Investigation of the depressants involved in the selective flotation of scheelite from apatite, fluorite, and calcium silicates: Focus on the sodium silicate/sodium carbonate system*. *Powder Technology*. 352, 501-512.
- FREE, M.L. and MILLER, J.D., 1996. *The significance of collector colloid adsorption phenomena in the fluorite/oleate flotation system as revealed by FTIR/IRS and solution chemistry analysis*. *Int. J. Miner. Process.* 48, 197-216.



- GAO, J., SUN, W., HU, Y., WANG, L., LIU, R., GAO, Z., CHEN, P., TANG, H., JIANG, W. and LYU, F., 2019. *Propyl gallate: A novel collector for flotation separation of fluorite from calcite*. Chemical Engineering Science. 193, 255-263.
- HU, Y. and XU, Z., 2003. *Interactions of amphoteric amino phosphoric acids with calcium-containing minerals and selective flotation*. International Journal of Mineral Processing. 72, 87-94.
- JONG, K., PAEK, I., KIM, Y., LI, I. and JANG, D., 2020. *Flotation mechanism of a novel synthesized collector from Evodiaefructus onto fluorite surfaces*. Minerals Engineering. 146,
- LEWANDOWSKI, B., SAID, B.B., ULBRICHT, M. and KREKEL, G., 2019. *Application of Raman spectroscopy to the flotation process of fluorite*. Minerals Engineering. 135, 129-138.
- LI, L., HAO, H., YUAN, Z. and LIU, J., 2017. *Molecular dynamics simulation of siderite-hematite-quartz flotation with sodium oleate*. Applied Surface Science. 419, 557-563.
- LIU, C., SONG, S. and LI, H., 2019. *Selective flotation of fluorite from barite using trisodium phosphate as a depressant*. Minerals Engineering. 134, 390-393.
- LIU, C., ZHOU, M., XIA, L., FU, W., ZHOU, W. and YANG, S., 2020. *The utilization of citric acid as a depressant for the flotation separation of barite from fluorite*. Minerals Engineering. 156,
- LIU, H., KHOSO, S. A., SUN, W., ZHU, Y., HAN, H., HU, Y., KANG, J., MENG, X. and ZHANG, Q., 2019. *A novel method for desulfurization and purification of fluorite concentrate using acid leaching and reverse flotation of sulfide*. Journal of Cleaner Production. 209, 1006-1015.
- MARINAKIS, K.I. and SHERGOLD, H.L., 1985. *The mechanism of fatty acid adsorption in the presence of fluorite, calcite and barite*. International Journal of Mineral Processing. 14, 161-176.
- MIELCZARSKI, E., MIELCZARSKI, J.A., CASES, J.M., RAI, B. and PRADIP, 2020. *Influence of solution conditions and mineral surface structure on the formation of oleate adsorption layers on fluorite*. Colloids and Surfaces A: Physicochemical and Engineering. 205, 73-84.
- SAYILGAN, A. and AROL, A I., 2004. *Effect of carbonate alkalinity on flotation behavior of quartz*. International Journal of Mineral Processing. 74, 233-238.
- SIS, H. and CHANDER, S., 2003. *Adsorption and contact angle of single and binary mixtures of surfactants on apatite*. Minerals Engineering. 16, 839-848.
- TASKER, P.W., 1980. *The structure and properties of fluorite crystal surfaces*. Le Journal de Physique Colloques. 41, C6-488-C6-491.
- TIAN, J., XU, L., SUN, W., HAN, H., ZENG, X., FANG, S., HONG, K. and HU, Y., 2019. *The selective flotation separation of celestite from fluorite and calcite using a novel depressant EDTA*. Powder Technology. 352, 62-71.
- TIAN, J., XU, L., SUN, W., ZENG, X., FANG, S., HAN, H., HONG, K. and HU, Y., 2019. *Use of  $Al_2(SO_4)_3$  and acidified water glass as mixture depressants in flotation separation of fluorite from calcite and celestite*. Minerals Engineering. 137, 160-170.
- VINCENT, B.V, 1999. Handbook of Monochromatic XPS Spectra: *The Elements of Native Oxides, BE Lookup Table for Signals* from Elements and Common Chemical Species. XPS International, Inc: Kawasaki, Japan.
- WANG, J., LI, W., ZHOU, Z., GAO, Z., HU, Y. and SUN, W., 2020. *1-Hydroxyethylidene-1,1-diphosphonic acid used as pH-dependent switch to depress and activate fluorite flotation I: Depressing behavior and mechanism*. Chemical Engineering Science. 214,
- WANG and HU, 1998. *Flotation solution chemistry*. Hunan Science and Technology Publishing House. (in Chinese)
- WANG, Z., WU, H., XU, Y., SHU, K., YANG, J., LUO, L. and XU, L., 2020. *Effect of dissolved fluorite and barite species on the flotation and adsorption behavior of bastnaesite*. Separation and Purification Technology. 237,
- XU, Y., XU, L., WU, H., TIAN, J., WANG, Z. and GU, X., 2020. *The effect of citric acid in the flotation separation of bastnaesite from fluorite and calcite using mixed collectors*. Applied Surface Science. 529,
- YANG, S., XU, Y., LIU, C., HUANG, L., HUANG, Z. and LI, H., 2020. *The anionic flotation of fluorite from barite using gelatinized starch as the depressant*. Colloids and Surfaces A: Physicochemical and Engineering Aspects. 597,
- ZHANG, Z.G., CAO, Y.J., LIAO, Y.F. and MA, Z.L., 2019. *Study on comparison adsorption of calcium and sulfate on scheelite and fluorite surfaces*. Separation Science and Technology. 54, 1247-1256.
- ZHENG, R., REN, Z., GAO, H., CHEN, Z., QIAN, Y. and LI, Y., 2018. *Effects of crystal chemistry on sodium oleate adsorption on fluorite surface investigated by molecular dynamics simulation*. Minerals Engineering. 124, 77-85.
- ZHOU, H., ZHANG, Y., TANG, X., CAO, Y. and LUO, X., 2020. *Flotation separation of fluorite from calcite by using psyllium seed gum as depressant*. Minerals Engineering. 159,

ZHU, H., QIN, W., CHEN, C., CHAI, L., JIAO, F. and JIA, W., 2018. *Flotation separation of fluorite from calcite using polyaspartate as depressant*. Minerals Engineering, 120, 80-86