Review

Evaluation of the replacement of NaCN with depressant mixtures in the separation of copper–molybdenum sulphide ore by flotation

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ABSTRACT

In the present study, we investigated the replacement of NaCN with pure depressant and depressant systems in the flotation separation of Cu-Mo bulk concentrate supplied by China Molybdenum Co., Ltd on a laboratory scale. The contrast experiments between the developed depressant system and NaCN were conducted in open circuit, and the results indicated that the developed depressant system achieved the similar Cu removal efficiency (cyanide 94.07% and developed reagent scheme 91.34%) and Mo recovery (cyanide 93.61% and developed reagent scheme 93.14%), which exhibited the advantages of environmental compatibility and economic adaptability. The results of FTIR spectra and XPS indicated that the chemical adsorption process may dominate the interaction of depressant with chalcopyrite, and a possible depressant mechanism is predicated along with a postulated adsorption mode for the surface interaction between disodium carboxymethyltrithiocarbonate (DMTC) and chalcopyrite.

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1. Introduction

Flotation, a physicochemical separation process that exploits the difference in the surface properties of valuable minerals and unwanted gangue minerals, is currently the most important and versatile mineral processing technique [1]. It utilizes the hydrophobic (aerophilic) nature of mineral surfaces and their tendency to attach to rising air bubbles in a water–ore pulp [2]. Hydrophobic particles are selectively attached and remain on the surface of gas bubbles rising through a pulp and are thus concentrated or separated from the pulp in the form of froth [3].

Chalcopyrite ($CuFeS_2$) and molybdenite (MoS_2) are the main copper and molybdenum minerals found in complex sulphide ores. The usual flotation practice of separating molybdenite from chalcopyrite relies on a two-stage flotation process [4,5]. First, a bulk Cu-Mo concentrate is produced, which is later refloated to obtain separate chalcopyrite and molybdenite products. This second selective stage requires the use of various depressants that destroy the collector coating around chalcopyrite particles (in addition to affecting the redox conditions of the pulp) and thus, prevent chalcopyrite flotation [5]. The selectivity of the process is greatly enhanced by the natural hydrophobicity of molybdenite, which is further increased in practice by the addition of an oily collector. In flotation processes, a number of chemicals ("reagents") are used. Each of these reagents has a serious impact on the environment, some greater, some lesser. Certain reagents used in the mineral flotation of non-ferrous metals (cyanides, xanthates, etc.) are strong poisons or carcinogens, and their decay creates harmful substances [6].

The China Molybdenum Co., Ltd., located in the Henan province, currently processes ores in amounts exceeding 30,000 t/d. Molybdenite concentrate is recovered as a main product over a two stage process. First, a bulk flotation concentrate of copper and molybdenum is produced using kerosene and 2# oil (pine oil) as collector and frother respectively; and in the Cu-Mo separation stage, sodium cyanide was adopted as a copper depressant. Cyanide is highly toxic, and this is related to its physicochemical characterization. The free cyanide form of HCN, CN^- is classified as the most toxic group, due to its high potential for metabolic inhibition [6,7]. When it is discharged in a tailing effluent, it causes serious environment pollution. The use of cyanide in flotation can also cause considerable losses in the values of gold and silver due to the strong complexing effect of cyanide with these precious metals. In excessive quantities, cyanide can be poisonous to humans and animals because it binds to the iron-carrying enzymes required for oxygen transport. In cases of cyanide poisoning, the body rapidly exhibits symptoms of oxygen starvation and suffocation [4]. In view of the above points, particularly the much stricter control of tailing effluent, the China Molybdenum Co., Ltd., has put considerable effort into seeking a replacement for cyanide that is equally as effective, but causes fewer pollution problems.

The use of depressant systems (combinations of different depressants) rather than a single depressant is widely practised in operating plants that treat massive sulphide ores. In practice, when treating complex sulphide ores, the use of two or more depressants is common, especially when a selectivity problem is present or separation of several valuable minerals is required [8–10]. Research and development work has been carried out to develop and define depressant systems for beneficiation of massive sulphide ores [8], arsenic-bearing minerals [11–14], and smithsonite-calcite-quartz ores [15]. In some cases, the performance of one depressant was greatly improved in the presence of another. This was mainly attributed to the conditions and environment changes created by the use of the two or more depressants [8].

The separation of molybdenite from a polymetallic ore is a challenging task, wherein a proper combination of reagents is needed to depress associated gangue minerals. In the present work, we evaluated the replacement of NaCN with depressant mixtures in the flotation separation of a Cu-Mo bulk concentrate on a laboratory scale. Moreover, a potential reagent regime was developed with the added advantages of environmental acceptability and increased economic viability. In previous micro-scale flotation research [4,16], pure minerals were used; while this study was based on a real Cu-Mo ore flotation separation.

2. Experimental

2.1. Materials

2.1.1. Cu-Mo bulk concentrate sample

The China Molybdenum deposit contains several billion tonnes of ore averaging 0.12% molybdenum and 0.015% copper. It is located in the middle part of China in Henan province and currently process 30,000 t/d. Molybdenum in the form of molybdenite is recovered from molybdenum concentrate as a main product in two stages. On the contrary, copper mainly in the form of chalcopyrite is recovered from molybdenum concentrate as a by-product in two stages. Therefore, the bulk concentrates processes characteristics of a higher grade of molybdenum but a lower grade of copper. The bulk concentrate, which was obtained from the China Molybdenum Co., Ltd, with 0.95% Cu and 7.23% Mo collected from a day shift, was used for the flotation separation of copper-molybdenum sulphides in all of the flotation tests. The mineralogical analysis results showed that both copper and molybdenum mainly existed in the form of chalcopyrite and molybdenite, respectively, and the gangue minerals were primarily quartz, biotite, muscovite, clay, fluorspar, chlorite, calcite, etc.

2.1.2. Chemical reagents

Disodium trithiocarbonate (DT) was prepared in house by a one-pot synthesis process [17] and used as a depressant without purification. The preparation of disodium carboxymethyltrithiocarbonate (DCMT) was carried out according to the literature [18] and used as a depressant. Kerosene and 2# oil (pine oil) supplied by the China Molybdenum Co., Ltd. were used as collector and frother, respectively. P-Nokes reagents (PN) were prepared by mixing phosphorus pentasulphide with sodium hydroxide in a
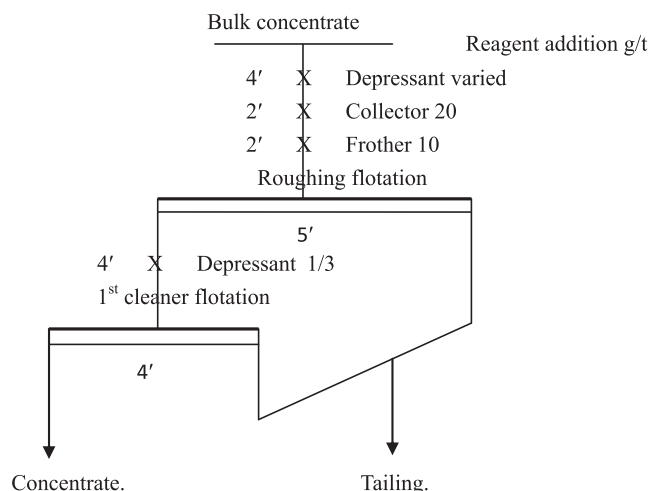

Fig. 1. The beneficiation flow sheet of conditional experiment.

mass ratio of 1:1.3. All of the chemicals (AR) used for preparation of depressants were purchased from the local supplier (Guoyao, China) and without further purification.

2.2. Methods

2.2.1. Chemical analysis
Spectrophotometric analysis of samples was conducted using standard methods for Mo analysis (752 UV visible single beam spectrophotometer, JingHua Instruments, China). Copper was determined by inductive couple plasma spectrometry (ICP-OES, Optima 8000DV/PerkinElmer, USA).

2.2.2. Flotation equipment
The bench-scale flotation tests were conducted in a series of flotation machines (XFD-1.5L, XFD-1.0L XFD-0.75L, XFD-0.5L, XFGC II ModelHanging Cell flotation Machine-0.4L), which were manufactured by Jilin prospecting machinery factory (China).

2.2.3. Flotation experiments
The experimental runs were conducted in an XFD type flotation cell with a volume capacity of 1.5 L. The feed sample was 100% passing a 0.150 mm size fraction (Fig. 2). The feed was added to the flotation cell with tap water to obtain a required pulp density. The pulp density (solid%) was adjusted to be 50% at conditioning and 33% during flotation. Next, the required amount of depressant was added and conditioned for four minutes. Subsequently, the measured amount of collector and frother were added in order and conditioned for two minutes. The air was turned on after two minutes of frother addition. The flotation time was 5 min according to the results of the previous experiment (not shown). The flow sheet and conditions of flotation tests are shown in Fig. 1. Both the concentrate and tailings were filtered, dried and weighed. Concentrate and tailings were analysed.

2.2.4. FT-IR spectra analysis
Fourier transform infrared (FT-IR) spectra of samples were recorded by a Bruker Alpha(Thermo, USA)FT-IR spectrometer at room temperature $(25 \pm 1\,°C)$ in the range from $400\,cm^{-1}$ to $4000\,cm^{-1}$ as KBr pellets. Prior to test, the chalcopyrite minerals (100% passing $-0.074\,mm$) approximately 95% purity (from Dexing copper Mine of Jiangxi province in China) were ground to less than $5\,\mu m$ in an agate mortar. Next, 0.5 g of the samples were added into 50 ml aqueous solution with or without 500 mg/L depressant at pH 10.5, and conditioned for 0.5 h. After that, the samples were filtered, three times washed with distilled water, and dried in a vacuum oven at room temperature for 24 h.

2.2.5. XPS analysis
The XPS spectra of the mineral particles were recorded with a K-Alpha 1063 (Thermo Scientific Co., USA) spectrometer with Al Ka as the sputtering source at 12 kV and 6 mA, with pressure in the analytical chamber at 1.0×10^{-12} Pa. All binding energies were referenced to the neutral C1 s peak at 285.0 eV to compensate for the surface-charging effects. The tested samples were obtained as follows. 0.5 g of mineral sample were added into 50 ml of the aqueous solution with or without 500 ppm depressant at pH 10.5, stir-

Table 2
Phase analysis of molybdenum (%).

Products	Sulphide mineral	Oxide mineral	Total molybdenum
Content	7.18	0.05	7. 23
Distribution	99.31	0.69	100.00

Table 3
Phase analysis of copper (%).

Products	Sulphide mineral	Oxide mineral	Total copper
Content	0.87	0.08	0.95
Distribution	91.58	8.42	100.00

red at 25 °C for 30 min, filtered, rinsed with distilled water and then dried under vacuum at room temperature for 24 h. The XPS were immediately recorded to calculate the surface compositions.

3. Mineralogy

3.1. Mineral composition

The polymetallic ore contains minerals such as molybdenite, pyrite, rutile, ilmenite and magnetite, sphalerite, malachite, chalcopyrite, chrysocolla, bornite, chalcocite, galena, cerussite, limonite, hematite, arsenopyrite, and scheelite. The gangue minerals mainly contain quartz, biotite, muscovite, potassium feldspar, a small amount of sodium feldspar, grossularite, calcite, fluorite, apatite, chlorite, sericite, kaolinite, and others.

3.2. Multi-element chemical and phase analysis

The multi-element chemical analysis results (Table 1) show that molybdenum and copper are the main available mineral resources, and the phase analysis results (Table 2) show that the 98.48% of the molybdenum is sulphide mineral, with the remaining 1.52% an oxide ore. The phase analysis results of copper presented in Table 3, the results indicate that copper bearing ores are mainly sulphide minerals.

3.3. Size distribution

The size of mineral particles plays a significant role in the sequence of events that lead to the flotation of a particle [2]. Due to its influence on flotation, particle size has been a subject of research for decades [19]. The size distribution of feed material (bulk concentrate) was determined by wet sieve method. A typical size distribution of the feed material is given in Fig. 2. It can be seen from the Fig. 2 that F80 and F50 of the bulk concentrate are approximately $60\,\mu m$ and $33\,\mu m$, respectively. In the present work, the size distribution of molybdenite and chalcopyrite were determined under microscope by line segment method and the results were shown in Fig. 2. The results indicated that both size of molybdenite and chalcopyrite were mainly distributed in the range of 0.074–0.025 mm, but molybdenite with finer size than chalcopyrite.

Table 1
Multi-element chemical analysis (%).

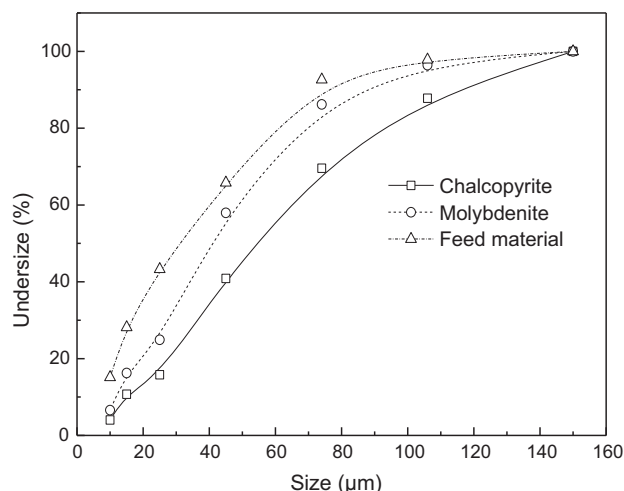| Component	Mo	Cu	Pb	Zn	Fe	CaO
Content	7.23	0.95	0.15	0.36	8.15	2.89
Component	MgO	Al_2O_3	SiO_2	K_2O	Na_2O	S
Content	2.35	6.87	56.89	1.52	0.47	6.35
Component	P	Ti	CaF_2	As	Bi	C
Content	0.15	0.26	1.02	0.016	0.025	0.37

Fig. 2. Size distribution of molybdenite, chalcopyrite and feed material.

4. Results and discussions

4.1. Tests on different pure depressants

In this study, the flotation process is evaluated by defining the removal efficiency, which as introduced by Mowla [20], η, is defined as follows:

$$\eta = \frac{C_i - C_f}{C_i} * 100\%$$

C_i and C_f are the initial and final copper concentration in the molybdenum concentrate, respectively.

The effect of various depressants on the Cu removal efficiency and Mo recovery are shown in Fig. 3. As seen in Fig. 3, as the depressant concentration increases, the removal efficiency of Cu increases and only a small effect on Mo recovery was observed. It could be seen that the removal efficiency of chalcopyrite presented similar trends, while using different depressants. Initially, the removal efficiency of chalcopyrite gradually increases with the increase of depressant concentration; however, the removal efficiency increases slowly when the depressant is increased to a certain concentration. For chalcopyrite, the maximal removal efficiency is 80.91%, 87.61%, and 91.96% with PN, DT and DCMT
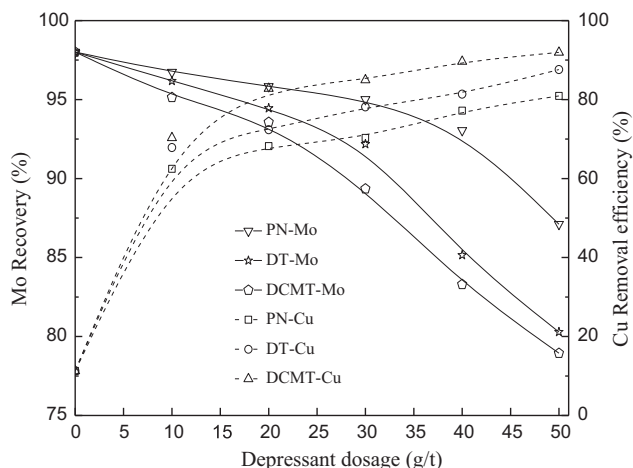

Fig. 3. Mo recovery versus Cu removal efficiency as a function of PN, DT, and DCMT concentration.
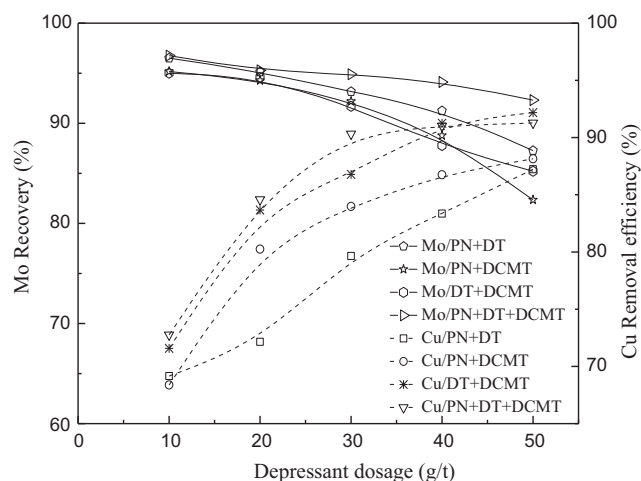

Fig. 4. Mo recovery versus Cu removal efficiency as a function of blend depressant concentration.

as depressants, respectively. For molybdenite, the recovery is 87.11%, 80.28% and 78.94% under these conditions. The results indicated that the Mo recovery was affected by the higher concentration of depressant, which may be explained by the fact that strongly alkaline solutions have a negative effect on molybdenite flotation [21]. Taking Cu removal efficiency and Mo recovery into consideration, the optimal concentration is 40 g/t, 30 g/t and 30 g/t with PN, DT and DCMT as pure depressant respectively. For the depressing capacity to chalcopyrite, the efficiency of the depressants is in descending order of DCMT and DT followed by PN. All three of the collectors, especially DCMT, show an excellent selectivity for chalcopyrite depression.

4.2. Combination of depressant

As mentioned above, the three depressants presented different depressing capacities for chalcopyrite. However, further efforts to adopt a single depressant to separate chalcopyrite from molybdenite failed. The process still faces some drawbacks: (a) the quality of the final Mo concentrate cannot meet the relevant quality standard; (b) pressure to produce marketable concentrate grades at the expense of recovery; (c) the complex beneficiation flow sheet and higher levels of depressant consumption. One of the major problems in the development of an effective reagent scheme for the treatment of a massive sulphide ore lies in finding an effective depressant system for differential flotation [8]. In light of these, a series of experiments were conducted using PN + DT, PN + DCMT, DT + DCMT and PN + DT + DCMT mixtures and the optimum concentrations were determined by a trial and error approach (mass ratio of 1:1 for the former three, and 1:1:1 for the latter one).

Fig. 4 shows the Cu removal efficiency and Mo recovery obtained from the tests performed using different concentrations of the reagent mixtures. The Cu removal efficiency steadily increases with the increases of depressant concentration, whereas the Mo recovery gradually decreased. The maximal Cu removal efficiency obtained is 87.23%, 89.15%, 92.13% and 91.28% for PN + DT, PN + DCMT, DT + DCMT and PN + DT + DCMT mixtures, respectively. Under the same conditions, the recovery of Mo is 87.27%, 82.35%, 85.21% and 92.31%, respectively. The reason may be due to the different nature of the reagents used. As indicated in the figure that as the increases of depressant, a larger amount of chalcopyrite was removed from the molybdenite. However, depressant quantities larger than 30 g/t of the feed in the cell seem to be not very effective on the removal efficiency. The removal efficiency decreased in the following order: PN + DT + DCMT > DT
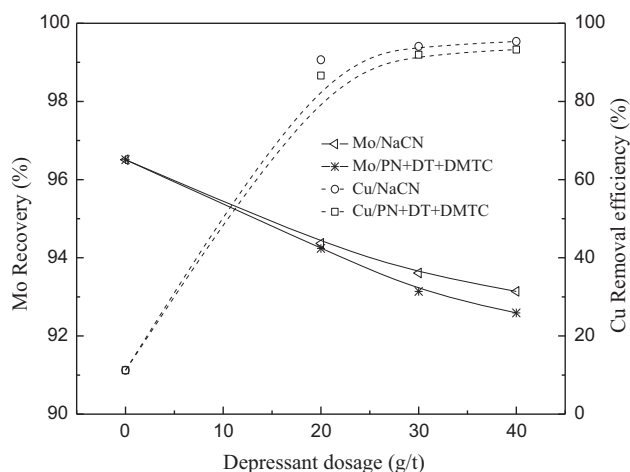
Fig. 5. Mo recovery versus Cu removal efficiency using the new depressant system and NaCN as depressant.

Fig. 6. FTIR spectra of chalcopyrite before and after depressant system treatment.

+ DCMT > PN + DCMT > PN + DT, with 90.32%, 86.78%, 83.98% and 79.65%, respectively. The recovery of Mo decreased in the following order; PN + DT + DCMT > PN + DT > PN + DCMT > DT + DCMT, with 94.89%, 93.16%, 92.19% and 91.69%, respectively. From a practical point of view, the depressant system is only effective when it provides good depression of a particular component without affecting the floatability of floated minerals. Therefore, the selectivity of mixtures (PN + DT + DCMT) is better than that of the other depressant system.

4.3. Contrast experiments of depressant

As stated in the previous section, it has been shown that either adopting pure depressant or appropriate depressant combinations can achieve significant improvement in copper removal efficiency results. However, since the purpose of this study is to evaluate the replacement of cyanide with other depressant in the flotation separation of Cu-Mo sulphide ores. Therefore, further test work was conducted on the flotation separation of chalcopyrite-molybdenite with cyanide and the developed depressant system (PN + DT + DCMT) through an open circuit. Fig. 5 compares Cu-Mo separation results obtained using the cyanide and the blend depressant methods. As the recovery of Mo is the primary objective of the flotation procedure it is of great importance to ensure that the use of blended depressants does not significantly alter the recovery of the floated mineral. The results show that the removal efficiency of chalcopyrite increases with the increasing amount of cyanide and blend depressants, but when the dosage reaches to 30 g/t, increasing the dosage of either cyanide or blend depressants have no obvious effect on the removal efficiency of chalcopyrite. With a depressant dosage of 30 g/t, the removal efficiencies of copper are 94.07% (cyanide) and 91.94% (blend depressant); the recoveries of molybdenite are 93.61% (cyanide) and 93.14% (blend depressant). In comparison to the use of cyanide alone, the developed depressant system achieved similar Cu removal efficiency and Mo recovery.
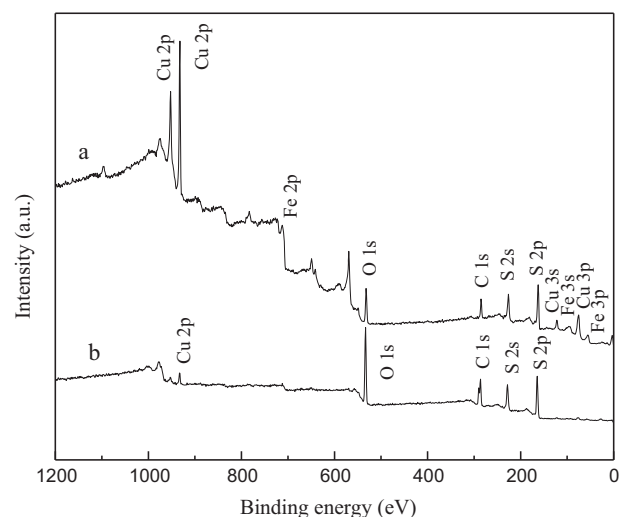

Fig. 7. The survey (full range) XPS spectrum of chalcopyrite before and after blend depressant treatment. (a) Before treatment, (b) after treatment.

4.4. Economic benefit analysis

The cost comparison of the two methods, only including reagent cost, is listed in Table 4. It is clear that the operational cost for the original method and the new process is 0.078 US $/ton and 0.070 US $/ton, respectively. Therefore, the new depressant system could ensure an efficient separation of the two minerals and save cost of 0.008 US $/ton for the plant. The flotation results indicate that the developed depressant system is feasible, promising and economical which can save the cost of reagent cost.

Table 4
Reagents cost comparison of the two methods (single vs. blend).

Depressant system	Chemical reagents	Dosage (g/ton)	Price (US $/ton)	Cost (US $/ton)	Total(US $/ton)
Single	NaCN	30	2600	0.078	0.078
Blend depressant	DT	10	2300	0.023	0.070
	PN	10	2200	0.022	
	DCMT	10	2500	0.025	
Δ[a]	/	/	/	/	0.008

Table 5
Atomic concentration of elements for chalcopyrite surfaces as determined by XPS.

Chalcopyrite	Chemical compositions (at%)				
	C1s	O1s	Fe3p	S2p	Cu2p
Treated	33.14	30.82	1.02	33.78	1.25
Untreated	22.21	16.91	8.98	31.14	20.76
Δ^a	10.93	13.91	−7.96	2.64	−19.51

Δ^a is defined as the value of after depressant treatment minus than that of before treatment.

4.5. FT-IR analysis

Fourier transform infrared (FTIR) spectroscopic measurements were used to delineate the potential mechanism by which reagents adsorb on mineral surfaces. Chalcopyrite samples treated and untreated with depressant system were subjected to infrared spectroscopic study in order to understand the interaction pattern and the spectra are shown in Fig. 6. As shown in Fig. 6, the new bands that appeared near 1633.70 cm^{-1}, 1328.9 cm^{-1}, 1006.8 cm^{-1}, and 667.4 cm^{-1} were due to C—O stretching, CH_2 wagging, C—S stretching and C—S stretching, which indicated the adsorption of depressant on the chalcopyrite surface. The adsorption of C—O, C—S and C—S groups on the chalcopyrite surface demonstrated that DCMT adsorbed on chalcopyrite surface which contains these functional groups in its molecular structure.

4.6. XPS analysis

To substantiate the chemical analysis provided by FTIR, XPS was performed on the treated and untreated chalcopyrite surface. XPS is a considerably more surface-sensitive technique compared to FTIR, science it characterizes the surface to a depth of less than 10 nm. Fig. 7 shows the survey scan spectra of chalcopyrite without (a) and with (b) depressant adsorption over a binding energy range of 1200–0 eV. The spectra show the expected elements on the chalcopyrite surface, such as C, O, S, Fe and Cu. The atomic surface of elements C1s, S2s, O1s, Cu2p/2s/3s/3p and Fe2p/3s/3p determined by XPS were summarized in Table 5. The results in Table 5 showed the atomic concentration ratios of S to Cu and Fe to Cu are 1.5 and 0.43, respectively, indicating that the surface of the untreated sample was slightly oxidized which is in good agreement with the report that iron oxide or hydroxides, or oxides of sulphur were present on the surface [22,23]. After depressant treatment, the atomic concentrations of C, O and S increased and those of Fe and Cu decreased, confirming the adsorption of depressant on chalcopyrite which consists with the FTIR results.

The good results obtained at a lower concentration may relate to the possible synergistic effect of the blend depressant due to the significant structural and charge differences (Fig. 8). Nokes Reagent, a product of the reaction of phosphorus pentasulphide with sodium hydroxide in a molar ratio of approximately 1:16 (mass ratio approximately 1:1.3), which contains a mixture of phosphorus compounds such as Na_3PS_4, Na_3PS_3O, $Na_3PS_2O_2$, Na_3PO_3S, Na_3PO_4, Na_2HPO_3, Na_2HPO_2S, Na_2S and NaHS [24,25]. A
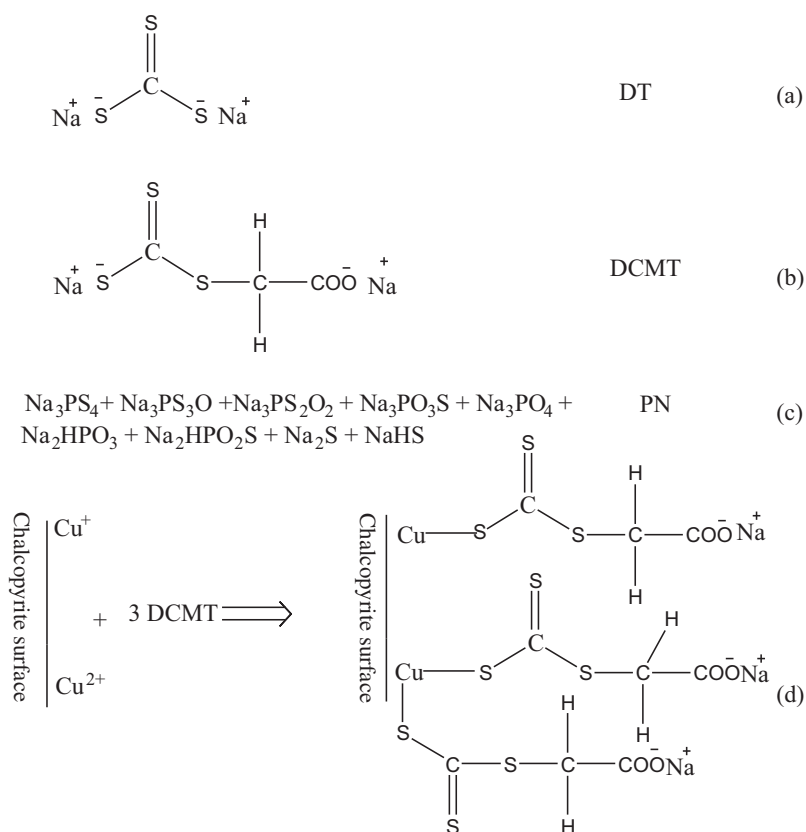
Fig. 8. Molecular structure of depressants (a, b and c) and adsorption mode of DCMT on chalcopyrite surface (d).

researcher predicted that the depression mechanism of Nokes reagent could be presented in two stages, (a) HS⁻ desorbs the adsorbed collector from the mineral surface; (b) the phosphorus compounds adsorb on the mineral surface to form a thin copper phosphorus film that is hydrophilic [26]. Unfortunately, we did not observe the P element presented in the XPS spectrum of the blend depressant treated chalcopyrite. According to the Δ^a value of C and O, a conclusion can be drawn that DMTC adsorbed on the chalcopyrite surface, which contains both C and O elements that increased after treatment. The Δ^a of Cu indicates that the copper ions presented on the oxidized surface of chalcopyrite might react with the depressant so that its concentration decreased remarkably (Table 5). It is interesting, that the atomic concentration of S increased which might be donated by DT (Fig. 8a), DMTC (Fig. 8b) or PN (Fig. 8c) because all of the molecular structures involve the S element. However, evidence from the pure depressant concentration tests demonstrated that PN and DT depress chalcopyrite strongly.

Mechanisms of sodium sulphide depressing chalcopyrite have been reported [27] that indicate the HS⁻ ions have more surface activating properties than xanthate ions, and therefore they could remove the collectors from the surfaces of the copper minerals. For DT (sodium trithiocarbonate), it hydrolyses and then dissociates and HS⁻ ions are formed and subsequently become the predominant ions under highly alkaline conditions. The new report [28] indicates that the mechanism involved when using a combination of sodium sulphide and sodium hydrosulphide as chalcopyrite depressant is accomplished through HS⁻ adsorption on chalcopyrite, to reduce the surface free energy of chalcopyrite then affect the adsorption of mixing hydrocarbon oil on chalcopyrite, therefore reducing the floatability of the chalcopyrite. Therefore, the adsorption mechanism of blend depressant cannot be elaborated clearly. However, a possible adsorption mode can be predicted as two stages, (a) PN and DT might desorb the adsorbed collector from the mineral surface through the hydrolysis product HS⁻ [26]; (b) DMTC with two polar groups such as $(-CS_3)^-$ and $-COO^-$, might adsorb on the surface of chalcopyrite thus reducing the floatability of chalcopyrite. It should be noted that the desorption of mixing hydrocarbon oil on chalcopyrite by PN and DT promotes the adsorption of DMTC and vice versa, which indicate that the effect of different depressants are not separate or sequential process, but might occur simultaneously. It is well known that $(-CS_3)^-$ react with chalcopyrite (copper ions) and adsorb on the mineral surface, which is in good agreement with the results of FTIR. On the contrary, $-COO^-$ is hydrophilic group which can exchange adsorption with mineral and form a layer of water molecules membrane between mineral and depressant to increase the hydrophilicity of the mineral surface, which is similar to that of sodium thioglycollate depress pyrite and chalcopyrite [29]. Therefore, a predicted depression mode is postulated for the surface interaction between the blend depressant and chalcopyrite (Fig. 8d).

5. Conclusions

In the present study, we carried out copper-molybdenum ore flotation experiments in the presence of pure and blend depressants. We investigated the ability of different depressant systems to substitute for NaCN in the selective flotation process on a laboratory scale. The results of tests employing different conditions indicated that chalcopyrite was significantly depressed using the new developed depressant system, PN:DT:DCMT in mass ratio of 1:1:1. Good Cu-Mo flotation separation results of contrast experiments test work were achieved, which demonstrated that the new depressant system is as effective as cyanide but causes fewer pollution problems. Unlike NaCN, the developed depressant system possesses lower toxicity with better environmental compatibility and economic adaptability. The mechanism of the blends can be proposed as occurring in two stages, (a) PN and DT might desorb the adsorbed collector from the mineral surface through the hydrolysis product HS⁻; (b) DMTC with two polar groups such as $(-CS_3)^-$ and $-COO^-$, might adsorb on the surface of chalcopyrite, thus reducing the floatability of chalcopyrite. The interaction of DMTC with the chalcopyrite surface consisted of a dominant chemisorption and this was confirmed by FTIR spectra and XPS. Therefore, a possible adsorption mode is proposed for the surface interaction between DMTC and chalcopyrite (Fig. 8d).

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