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Magnetic seeding depression in flotation of hematite ore slimes

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Abstract: Magnetic seeding depression (MSD), i.e. adding organic depressant (such as starch) and magnetic seeds and applying a low field intensity pre-magnetization for depressing target mineral in flotation, was investigated in the reverse flotation of hematite ore slimes. Flotation tests found that the iron recovery increased with the addition of magnetic seeds; the depressing ability of starch in flotation was further enhanced by the MSD. The increased adsorption density of starch on target mineral hematite and apparent size enlargement of fine minerals are two reasons for the MSD. Based on FTIR, VSM and AFM measurements it was demonstrated that the starch acted as a bridging adsorption between hematite and magnetic seeds by hydrogen bonding and chemisorption, and resultant coverage of the magnetic seeds and starch on hematite increased the magnetic susceptibility, being beneficial to the agglomeration of hematite fines by reducing the external magnetic intensity needed for agglomeration to take place. The model of the MSD was proposed.

Keywords: magnetic seeds, magnetic seeding flotation (MSF), magnetic seeding agglomeration (MSA), magnetic seeing depression (MSD), hematite

1. Introduction

Flotation is a famous technique in mineral processing. However, the conventional flotation was limited to its properly-sized range of 5-300 μm (Wills and Napier-Munn, 2006). The main reason behind this limitation lies in that owing to their huge specific surface areas fine mineral particles need relatively high dosage of reagents (especially collectors) and exhibit poor flotation performance while intermediate or properly-sized particles produce high flotation kinetics with low consumption of collectors. To improve the fine flotation performance quite a few of flotation methods have been investigated. Most of them are based on particle aggregation, namely, by enlarging the apparent particle size, such as carrier flotation, selective flocculation, shear flocculation, oil agglomeration flotation (Laskowski and Lopez-Vladivieso, 2004), temperature responsive polymer flocculation flotation (Forbes, 2011), and etc. However, these techniques are studied mainly for the direct flotation of fine minerals, and yet most of these techniques have not been successfully used in mineral processing.

Nowadays lean and fine-disseminated iron ores have become one of main resources for beneficiation industry. Meanwhile, much attention is attached to reverse flotation as a significant commercial separation process using polysaccharide as depressant for iron minerals and amine as collector for silica (Ma et al., 2011; Filippov et al., 2010). In the reverse flotation, the depressant (such as starch or its derivatives) is adsorbed onto iron minerals forming hydrophilic films, and then produces its depressing effect on the iron minerals (Turrer and Peres, 2010). Furthermore, Xia et al. (2009) reported that hydrogen bonding adsorption is considered as a universal adsorption model for starch in the depressing process of the reverse flotation.

There are two main types of starch: amylopectin and amylose. The amylopectin starch usually produces strong depression on the flotation (Weissenborn et al., 1995; Kar et al., 2013) and specially exhibits better depressing action on iron minerals. However, as the depressant for fine iron minerals starch is consumed too much due to high specific surface area of fines. In order to strengthen the adsorption of starch on iron minerals and reduce its consumption in flotation, starch has been modified

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through different techniques (Tharanathan, 2005; Kaur et al., 2012), such as various chemical, physical and compound modifications, and among them the chemical modification is one of the most widely used modification methods, and their modified products, such as dextrin, carboxyl methyl starch, the oxidized starch and phosphate ester starch, have been widely reported only for laboratory studies, but industrially causticized starch has been widely applied in the flotation of reverse iron ore flotation (Liu et al., 2006; Filippov et al., 2014; Tang et al., 2012, 2016). In fact, the causticization technique, on one hand, is to prepare the starch for flotation by conditioning the starch with some alkali solution (Peres and Correa, 1996; Weissenborn et al., 1996); on the other hand, mixtures of carboxylic acids were found in the caustic starch (Niemelä, 1990; Jebber et al., 1996). So, besides the hydroxyl groups, the existence of active carboxylic groups would further facilitate the adsorption of starch onto iron minerals including hematite, magnetite or magnetic seeds concerned in this study.

As mentioned above, reverse flotation of iron ore slimes consumes too much caustic starch due to large amount of fine minerals, and new methods should be introduced to strengthen the adsorption of starch onto iron mineral particles and reduce the dosage of starch. Song (1992) reported 'magnetic seeding flocculation' to flocculate weakly magnetic mineral particles with magnetite particles by adding a particular type of flocculants, but its huge consumption of magnetic seeds was as large as up to 10 kg/Mg. Recently a new technique called as 'magnetic seeding flotation (MSF)' has been introduced (Wu et al., 2016a, 2016b, 2016c), claiming that it was used well for fine flotation by magnetic seeding agglomeration (MSA), and it reduced the consumption of reagents. In comparison with the conventional flotation and its derivative techniques, the method the MSF differs mainly in that the magnetic seeds and pre-magnetization are brought in the conditioning of the slurry prior to aeration of flotation. In this study magnetic seeding depression (MSD), i.e. adding magnetic seeds (100-200 g/Mg), macromolecular depressant (such as starch), and pre-magnetization for flotation, was investigated via flotation tests and measurements to demonstrate that magnetic seeding depression can produce a strong flotation depressing action via introducing the magnetic interactions and the bridging adsorption of starch between fine particles in a suspension.

2. Materials and Methods

2.1. Materials

Hematite ore slimes collected from an iron ore mine in Gansu province, China, assaying 43.73% Fe (total) and 24.11% SiO_2 respectively, were used for flotation tests. Its particle size is 96.70% -15 µm, and the sample is not suitable for flotation. Pure hematite with an average granularity of 17.11 µm was obtained from the above ore slimes by high-intensity magnetic separation and gravity separation and was mainly used for the investigation of the magnetic seeding depression (MSD). Chemical compositions of the sample used are given in Table1.

Table 1. Chemical compositions of material used

Sample	Fe_2O_3 (%)	SiO_2	Al_2O_3	CaO	MgO	LOI
Hematite ore slimes	60.21	24.11	5.21	2.82	3.49	4.45
Pure hematite	98.02	0.7	0.5	0.07	0.04	0.47

Potato starch, commercial product, was conditioned with a ratio of 4 parts starch to 1 part sodium hydroxide by boiling the mixture for about 20 min while stirring in the air atmosphere. The solution, so-called 'caustic starch', was diluted as a 20 mg/cm^3 concentration. Dodecylamine (DDA) was used as the collector for flotation.

Magnetic seeds were produced through the air-oxidation technique (Wu et al., 2013). Reagents of moderate Fe(II) salts in deionized water and $NH_3{\cdot}H_20$ were added to the system at 85 °C while stirring. About 35 min later, the solution of magnetic seeds was synthesized with an average size of 100-200 nm. It is worth noting that the magnetic seeds with a high specific magnetic susceptibility should be fully dispersed by an ultrasonic cleaner prior to use due to their self-agglomeration.

In this study, a stirring pre-magnetizer, as designed in Fig. 1a, was used to produce a background magnetic field (10-300 mT) for pre-magnetizing the flotation pulp. In addition, a mini pre-magnetizer was also designed to prepare the pre-magnetization for agglomeration analysis with the magnetic field intensity range of 40-80 mT, as illustrated in Fig. 1b.

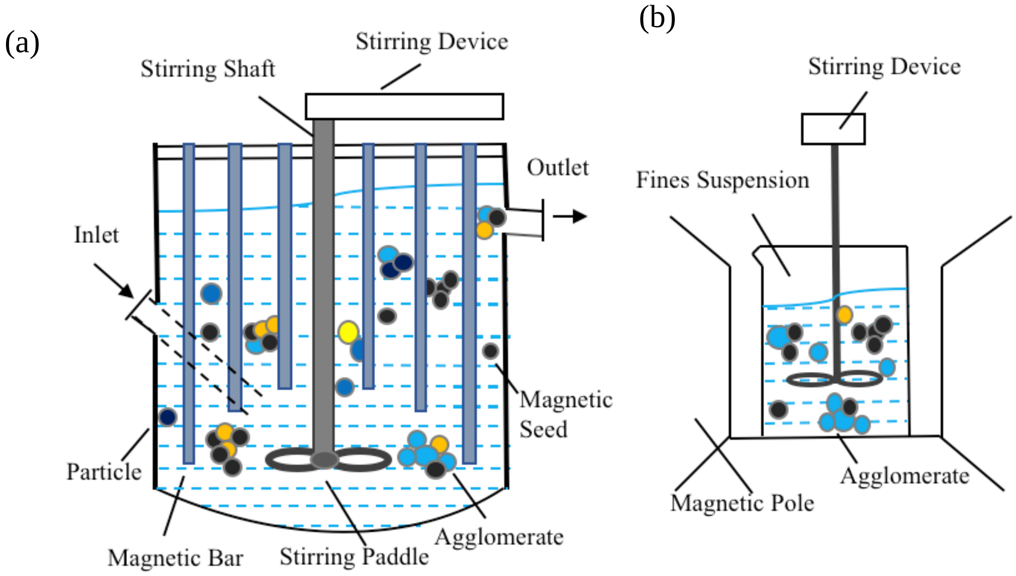

Fig. 1. Pre-magnetic devices for flotation test and the agglomeration analysis: (a) stirring pre-magnetizer, (b) mini pre-magnetizer

2.2 Magnetic seeding flotation (MSF)

Each test sample of 180 g hematite ore slimes was dispersed with tap water and conditioned in the above stirring pre-magnetizer (its volume 500 cm^3) for 3 min after adding magnetic seeds. Following the magnetic seeds, other reagents were added into the pulp and conditioned for 4 min. Then the pulp was introduced to the flotation cell (500 cm^3) for flotation. In this reverse magnetic seeding flotation, the target mineral hematite is depressed as a sunk product rather than floated, and here this process is specially called 'magnetic seeding depression (MSD)'.

2.3 Total Organic Carbon (TOC) analysis for measuring adsorption

To obtain the coating intensity of the caustic starch (initial concentration: 0.5 mg/cm^3) onto hematite, two samples of 40 cm^3 hematite suspension (5.0 wt%) were prepared firstly, both the blank and the control samples of the hematite suspension were conditioned with the same caustic starch solution of a certain concentration, but with the addition of a 0.02 mg/cm^3 magnetic seeds solution for the control group under the pre-magnetization. Finally, a part of the mixture was centrifuged and a 25 cm^3 aliquot of the supernatant in the centrifuge tube was transferred to the TOC-L$_{CPH}$ analyzer (SHIMADZU, Japan) for TOC analysis, and the adsorption density was calculated from the following equation.

$$\Gamma = \frac{C_i - \frac{0.5C_{toc}}{C_{ts}}}{M} \quad (1)$$

where Γ represents the adsorption density (mg/g); C_i is the initial concentration (mg/cm^3) of starch in the suspension; C_{toc} is related to the TOC analysis value (mg/cm^3) of the supernatant and C_{ts} (mg/cm^3) is regarded as the TOC analysis value of the 0.5 mg/cm^{3}caustic starch solution; M (g/cm^3) refers to the concentration of hematite sample (actual value is 50 mg/cm^3).

2.4 Particle size analysis for the agglomeration by laser diffraction

The hematite suspensions (5.0 wt%) after adding 1 mg/cm^3 starch and/or 0.2 mg/cm^3 magnetic seeds, were transferred to the mini pre-magnetizer for pre-magnetization, and then were investigated for size analysis through the analyzer Mastersizer 2000. It was worth noting that the stirring speed of the analyzer should be less than 1000 r/min due to the unsteady or fragile agglomeration, and the ultrasonic of the analyzer should be turned off, too.

2.5 VSM measurements for fine minerals

The magnetisms of the pure hematite and the hematite conditioned with the magnetic seeds were obtained by the magnetometer Lake Shore 7404. The samples of hematite coated with a desired amount of magnetic seeds (10, 100, 1000 g/Mg) were prepared through stirring the hematite and magnetic seeds under the pre-magnetization for 5 min. Then, the suspension was introduced into the magnetic separation tube (150 mT) to discard those unabsorbed magnetic seeds, and the passing tailings were finally used for the VSM analysis (see Wu et al., 2012).

2.6 Atomic Force Microscope (AFM) study

The interaction forces between the magnetic seeds and the mineral substrate were measured by a Multimode SPM Atomic Force Microscope (AFM). The substrate surface of hematite or quartz with high purity was produced by slicing, lapping, polishing, and then using deionized water, alcohol and deionized water to wash it sequentially, and at last drying the surface by nitrogen. Glass fiber with a 10-μm-diameter magnetic seeding aggregate was manipulated to stick to the tip of the probe by epoxy resin. Probe with the magnetic seeds aggregate and substrate surface (hematite or quartz) were fixed to the corresponding positions of the AFM. Start button was pushed to make the probe move to, contact with and remove from the substrate surface. The corresponding picture and data were recorded by the computer automatically.

2.7 Fourier transform infrared spectroscopic (FTIR) characteristics

To study the adsorption characteristics between the caustic starch and minerals (hematite and magnetic seeds), the FTIR spectra were measured via the transmission method using the spectrometer Nicolet-thermo 750. A caustic starch solution of 1% (i.e. 10 mg/cm^3) was prepared, and then the pure hematite (minus 2 μm) and magnetic seeds conditioned with the caustic starch solution in the thermostatic shaker for 20 min at the temperature of 25 °C were prepared, respectively. A small part of the suspension was collected for centrifugation and the precipitates were dried at 55 °C using a vacuum drying oven. Finally, the FTIR studies were carried out on these samples.

2.8 Scanning Electron Microscope (SEM) imaging

Samples of 2 g pure hematite in the size range 10-20 μm were prepared firstly by the elutriation method, and then dispersed in 50 cm^3 deionized water for 2 min at room temperature. Then the reagents (caustic starch, magnetic seeds) were added to the suspension, and suspensions of hematite, hematite mixed with 0.2 mg/cm^3 caustic starch, and hematite mixed with 0.2 mg/cm^3 caustic starch and 0.18 mg/cm^3 magnetic seeds under the pre-magnetization were prepared. After conditioning, the dried samples with gold powder were prepared for SEM imaging by the Model JSM-6360LV (JEOL Corporation, Japan).

3. Results and Discussion

3.1 Magnetic seeding depression (MSD) in flotation

The sample of hematite ore slimes with a particle size of 96.70% -15 μm is fine and not suitable for the conventional flotation. To compare the conventional flotation with the magnetic seeding flotation, batch reverse flotation tests were carried out, as shown in Figs. 2 and 3.

In general, the fine and ultrafine hematite particles easily go away by entrainment (Wang et al., 2015). The Fe flotation recovery of the slimes with no magnetic seeds is only 51.50% as shown in Fig .2. The flotation recovery (or apparent flotation depression) of iron minerals was enhanced with the addition of magnetic seeds and the low field pre-magnetization. The iron recovery was raised with the increase of the seeds with an optimum recovery of 56.79 % by using 180 g/Mg magnetic seeds. Then Fig. 3 suggested that the increased pre-magnetization intensity was beneficial to the flotation recovery with an optimum intensity of about 50 mT, but beyond that intensity the recovery decreased with further increase of magnetic intensity, and this might be attributed to the particular self-agglomeration of the added magnetic seeds themselves under the higher magnetic field. So, a moderate pre-magnetization for the flotation is also needed here.

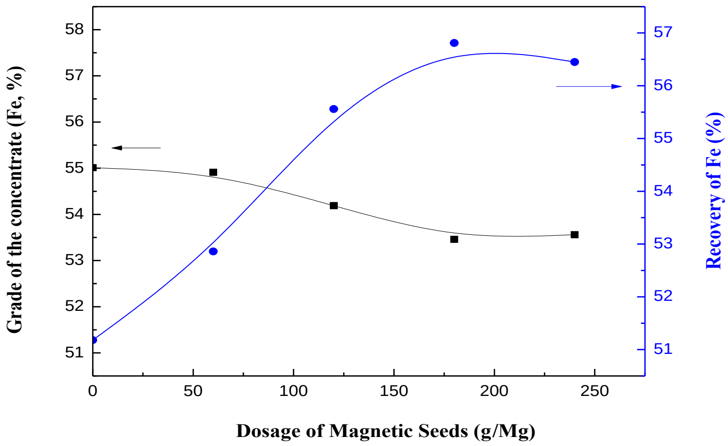

Fig. 2. Effect of magnetic seeds on the reverse cationic flotation performance of hematite ore slimes (collector DDA 400 g/Mg, caustic starch 1500 g/Mg, pre-magnetization at about 50 mT)

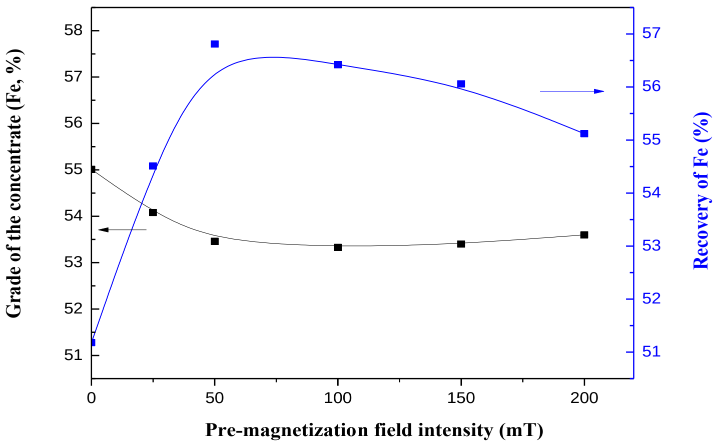

Fig. 3. Effect of the pre-magnetization field intensity on the flotation performance of hematite ore slimes (collector DDA 400 g/Mg, caustic starch 1500 g/Mg, magnetic seeds 180 g/Mg)

3.2 Adsorption of starch onto hematite

Measurements of the adsorption amount of caustic starch onto hematite with and without the addition of magnetic seeds were carried out, as recorded in Fig. 4.

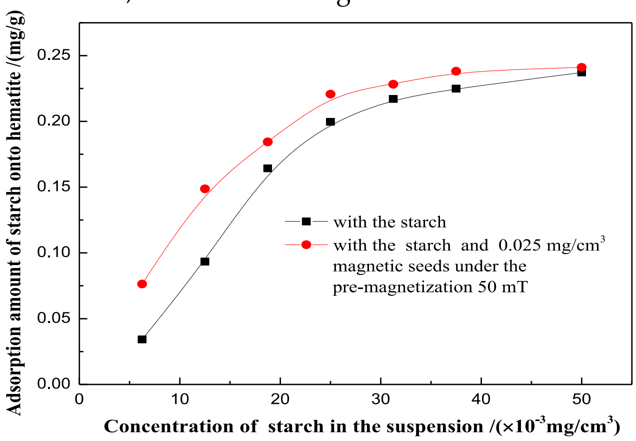

Fig. 4. Adsorption amount of starch onto hematite

It was found from Fig. 4, the adsorption intensity of starch onto hematite increased with the increase of starch concentration with the saturated adsorption amount of 0.237 mg/g (equivalent to 11.857×10^{-3}

mg/cm^3), and by contrast the adsorption was strengthened after the addition of 0.025 mg/cm^3 magnetic seeds. Also, according to Fig. 4, under the condition of a small starch concentration 25×10^{-3} mg/cm^3 the adsorption amount increased from 0.199 to 0.221 mg/g after adding magnetic seeds, so the stronger depression in the MSD might be attributed to the enhanced adsorption of starch onto iron minerals.

3.3 Size analysis for the agglomeration of hematite fines

It was found that the MSD particularly affected the starch adsorption onto hematite. Also due to the well-known flocculation of starch for fine hematite particles, the apparent size changes of the fine suspensions were analyzed for study on the agglomeration of particles. Then, the effects of magnetic seeds on the apparent size of fines under conditions of blank, caustic starch, and caustic starch with the magnetic seeds under the low field pre-magnetization were measured and given in Fig. 5 and Table 2.

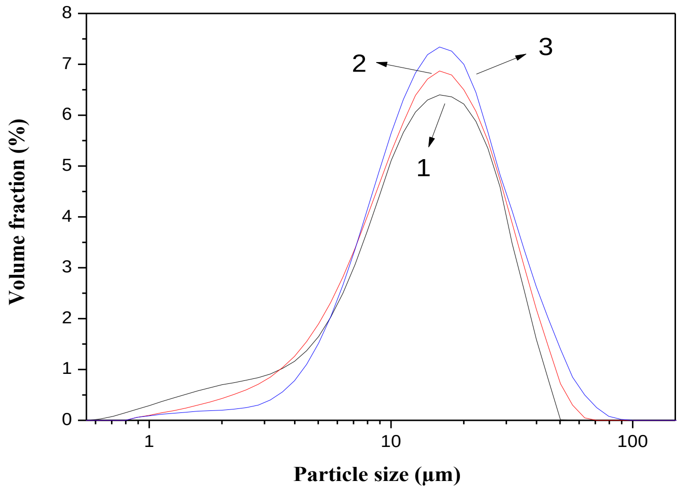

Fig. 5. Size distribution of pure hematite at natural pH; 1- blank. 2- 0.8 mg/cm^3 caustic starch. 3- 0.8 mg/cm^3 caustic starch + 0.12 mg/cm^3 magnetic seeds and the pre-magnetization at 50 mT

Table 2. Effect of magnetic seeds on the particle size of pure hematite

Sample	D(0.1), μm	D(0.5), μm	D(0.9), μm	Average size, μm
Hematite	4.67	15.32	32.08	17.11
Hematite + 0.8 mg/cm^3 starch	5.56	15.47	33.31	19.72
Hematite + 0.8 mg/cm^3 starch and 0.12 mg/cm^3 magnetic seeds, pre-magnetization at 50 mT	6.83	16.06	34.96	20.40

It can be seen in Fig. 5 and Table 2, the apparent granularity of hematite rose to 20.40 μm after adding magnetic seeds along with the starch while in the blank and the presence of the starch their average particle sizes were 17.11μm and 19.72 μm, respectively. So, it can be inferred from Table 2 that the hematite fines were flocculated after adding moderate starch which is a well-known flocculant, and the hematite fines were further agglomerated well in the case of presence of both starch and the magnetic seeds, i.e. the agglomeration of the starch with magnetic seeds and fine hematite particles under the pre-magnetization, so-called 'magnetic seeding agglomeration', might take place. Although after the agglomeration the overall average size displayed a slight increase from 19.7 to 20.4 μm only, but the ultrafine size of D(0.1) was increased by 22.84% (from 5.56 to 6.83 μm,) as shown in Table. 2, i.e. the ultrafine particles (most vulnerable faction to loss by the entrainment) in the suspension were greatly agglomerated by the MSD.

3.4 The threshold magnetic field intensity B_A for hematite fines to agglomerate

It is known that the total potential energy of a fine suspension plays an important role on its stability. Also based on the expanded DLVO theory to a fine suspension (Svoboda, 1982), the magnetic interaction

V_M is an essential part for the total energy V_T and the volume magnetic susceptibility x of particles is an important factor for the magnetic attraction in the external magnetic field B_o (the magnetic induction of pre-magnetization mentioned in this study). While the particles were placed in the external magnetic field, the calculation of V_M was given below (Svoboda, 1982):

$$V_M = -\frac{32\pi^2 R_0^6 \chi^2 B_0^2}{9\mu_0 d^3} \tag{2}$$

where R_o represents the radius of particles; B_o is the magnetic induction; x is the volumetric magnetic susceptibility of the particles; μ_o is the permeability of vacuum and d is related to the distance between particles.

So, the fine suspension would be instable due to the pre-magnetization B_o and the increased magnetic susceptibility x. To probe the agglomeration, VSM analysis and related calculation of the hematite coated by magnetic seeds were given as follows.

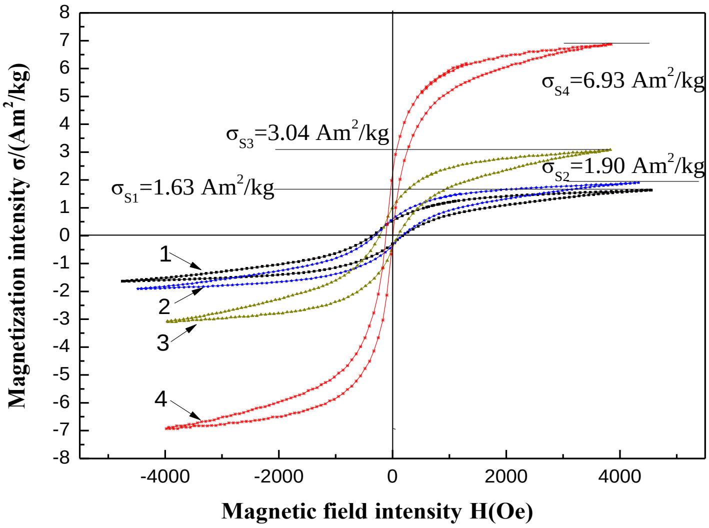

Fig. 6. Magnetic hysteresis loops of hematite; 1-hematite, 2-hematite-10 g/Mg magnetic seeds, 3- hematite-100 g/Mg magnetic seeds, 4- hematite-1000 g/Mg magnetic seeds

It can be seen in Fig. 6 that the hematite shows a weak specific saturation magnetization of 1.63 Am^2/kg. After the coverage of 10 g/Mg, 100 g/Mg and 1000 g/Mg magnetic seeds, its saturation magnetic induction increased to 1.90 Am^2/kg, 3.04 Am^2/kg and 6.93 Am^2/kg, respectively. A small amount of magnetic seeds coating onto hematite leads to a significant magnetic susceptibility change, promoting the magnetic seeding agglomeration.

Based on the Eq. (2), it is suggested that the external magnetic field B_o is a decisive factor for fine particles to agglomerate. Watson (1976) proposed a method to analyze the threshold magnetic field intensity B_A for fine particles to agglomerate below:

$$B_A = \left(\frac{2KT\mu_0}{\pi^2 \chi^2 R_0^3}\right)^{1/2}. \tag{3}$$

Here, K is the Boltzmann constant; μ_o is $4\pi\times10^{-7} N/A^2$; T = the degree Kelvin; R_o = the radius of mineral particle, and x is the volume magnetic susceptibility of the target mineral. The related results were shown in Table 3.

Table 3. Threshold magnetic field intensity B_A for hematite fines to agglomerate (R_o = 8 μm)

Sample	σ_s, Am^2/kg	x (10^{-6})	B_A, mT
Hematite	1.63	123.76	11.56
Hematite with 100 g/t magnetic seeds	3.04	284.65	5.03

It can be observed from Table 3 that the threshold magnetic field intensity for hematite to agglomerate decreased dramatically after adding magnetic seeds. Here it is noteworthy that the condition B_A only represents a necessary condition for the initiation of magnetic agglomeration (or flocculation). Shao et al. (1996) showed that when the pre-magnetic field intensity was more than 100 mT, the true agglomeration efficiency of a hematite sample (without magnetic seeds) with a size of -23 μm increased after stirring at a slow stirring speed of 400 r/min for 15 min. In this study, the actual magnetic susceptibility of hematite increased by the addition of magnetic seeds coated onto hematite particles, and then the increased magnetic susceptibility decreased the threshold magnetic field intensity and facilitated the magnetic seeding agglomeration in a quite low external magnetic field in the pre-magnetizer.

3.5 The interaction forces between particles by AFM

The AFM was used to investigate the interaction forces, and these forces between a magnetic seeding aggregate and substrate surfaces (hematite and quartz) were obtained in the dry atmosphere and recorded in Fig. 7.

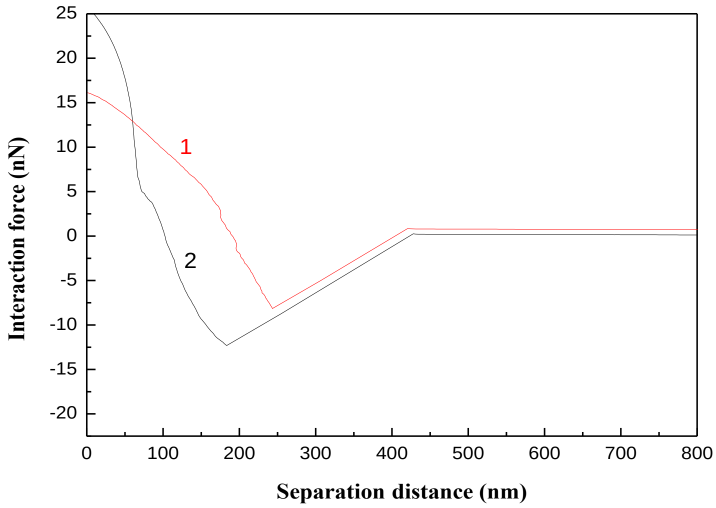

Fig. 7. Interaction force between a 10-μm-diameter magnetic seeding aggregate and a flat substrate surface in dry atmosphere; 1 – quartz substrate, 2 – hematite substrate.

As shown in Fig. 7, the attractive force can still be measured even the separation distance is more than 200 nm and the maximum value of the attractive force is up to 10 nN. So, the force can be characterized as a long-range force due to high magnetic energy in the presence of the magnetic seed. This long-range force would greatly strengthen the adsorption of magnetic seeds onto fine minerals and increase the magnetic susceptibility of fines, and then help the agglomeration of fine particles to happen under the condition that the particles were placed in the external magnetic field (Svoboda, 1982).

3.6 FTIR spectra study of fine particles conditioned with the caustic starch

FTIR spectra of the starch, hematite, magnetic seeds, precipitates (hematite-caustic starch) and (magnetic seeds-caustic starch) were obtained and given in Fig. 8 and Fig.9.

As shown in Fig. 8, in the spectrum of hematite conditioned with the caustic starch the new adsorption nearing 1031 cm^{-1} is the C-O stretching and C-OH bending vibration, and the peak around 1070 cm^{-1} can be assigned as the C-H bending vibration, and the small COO^- asymmetric and symmetric stretching bands (Tang et al., 2012) are found around 1625 and 1404 cm^{-1}. However, the COO^- peaks are small, indicating the low concentration of the carboxyl groups. The peak around 3419 cm^{-1} is the stretching vibration of O-H group, indicating the presence of hydrogen adsorption on the hematite. After the adsorption, the adsorption bands nearing 561 and 467 cm^{-1} are shifted to 538 and 457 cm^{-1} respectively, suggesting the hematite-starch interaction. These highlight that the starch was mainly absorbed onto the hematite via the hydrogen bonding adsorption and chemisorption.

It can be also inferred from Fig. 9 for the spectrum of magnetic seeds treated with the caustic starch, the new bands around 1634 and 1400 cm^{-1} are due to the COO^- asymmetric and symmetric stretching adsorption (Tang et al., 2012), demonstrating the chemisorption of caustic starch onto magnetic seeds, and the C-O stretching and C-OH bending vibration at 1028 cm^{-1} and the adsorption around 1072 cm^{-1} regarded as the C-H bending vibration are also observed. Another peak around 3423 cm^{-1} is attributed to the O-H stretching vibration. Like the adsorption onto hematite, the starch was also absorbed onto the magnetic seeds through the hydrogen bonding adsorption and chemisorption.

Therefore, the starch was adsorbed onto the magnetic seeds and hematite. In this way, the starch adsorption acts as a bridging media between the two types of particles, resulting in an intensified coverage of the starch onto hematite particles and positive action in the agglomeration via the pre-magnetization. The proposed model of the MSD is illustrated in Fig. 10.

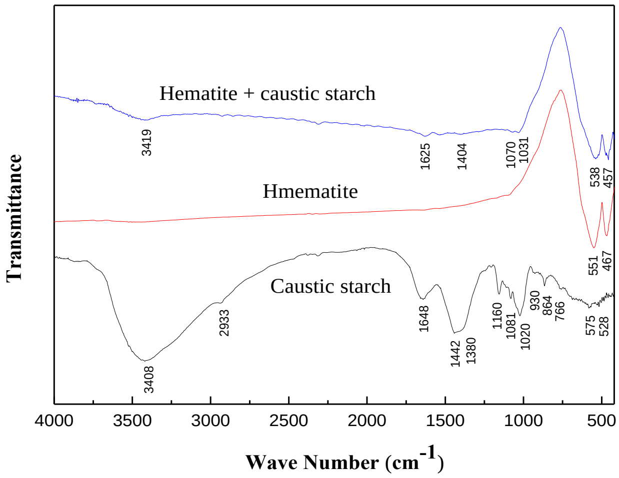

Fig. 8. FTIR spectra of caustic starch, hematite and hematite conditioned with caustic starch

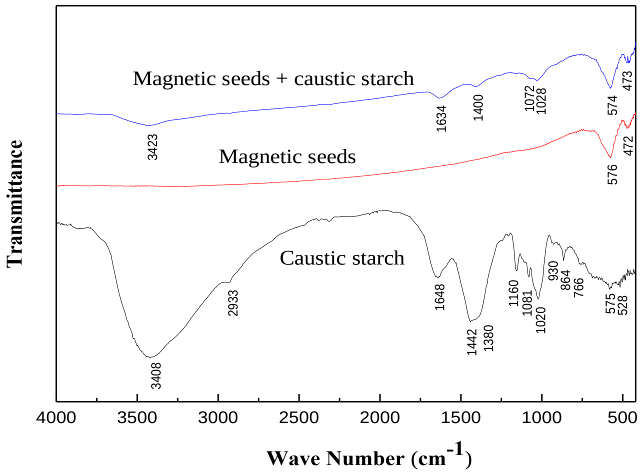

Fig. 9. FTIR spectra of caustic starch, magnetic seeds and magnetic seeds treated with caustic starch

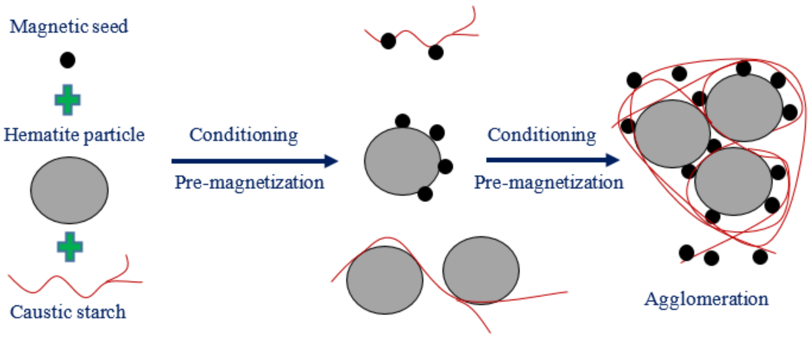

Fig. 10. Proposed model of the MSD for fine hematite particles

3.7 Surface characterization (SEM imaging)

In order to further probe the adsorption surface morphology of the magnetic seeding depression, SEM images are presented in Fig. 11. Fig. 11(a) shows the uniform characteristic of magnetic seeds in the size range 100-200 nm, and in Fig. 11(b) the agglomerates of most magnetic seeds are adsorbed onto hematite although a relatively small number of single magnetic seeds are scattered on hematite surface. The morphologies of starch and its adsorption onto hematite are given in Fig. 11(c) and (d) respectively. Then the agglomeration of magnetic seeds and starch with the hematite can be seen in Fig. 11(e) and (f), and the starch is absorbed onto the hematite prior to the magnetic seeds and the agglomerates of magnetic seeds are found outside the adsorption layer of the starch which acts as the bridging media between hematite and magnetic seeds.

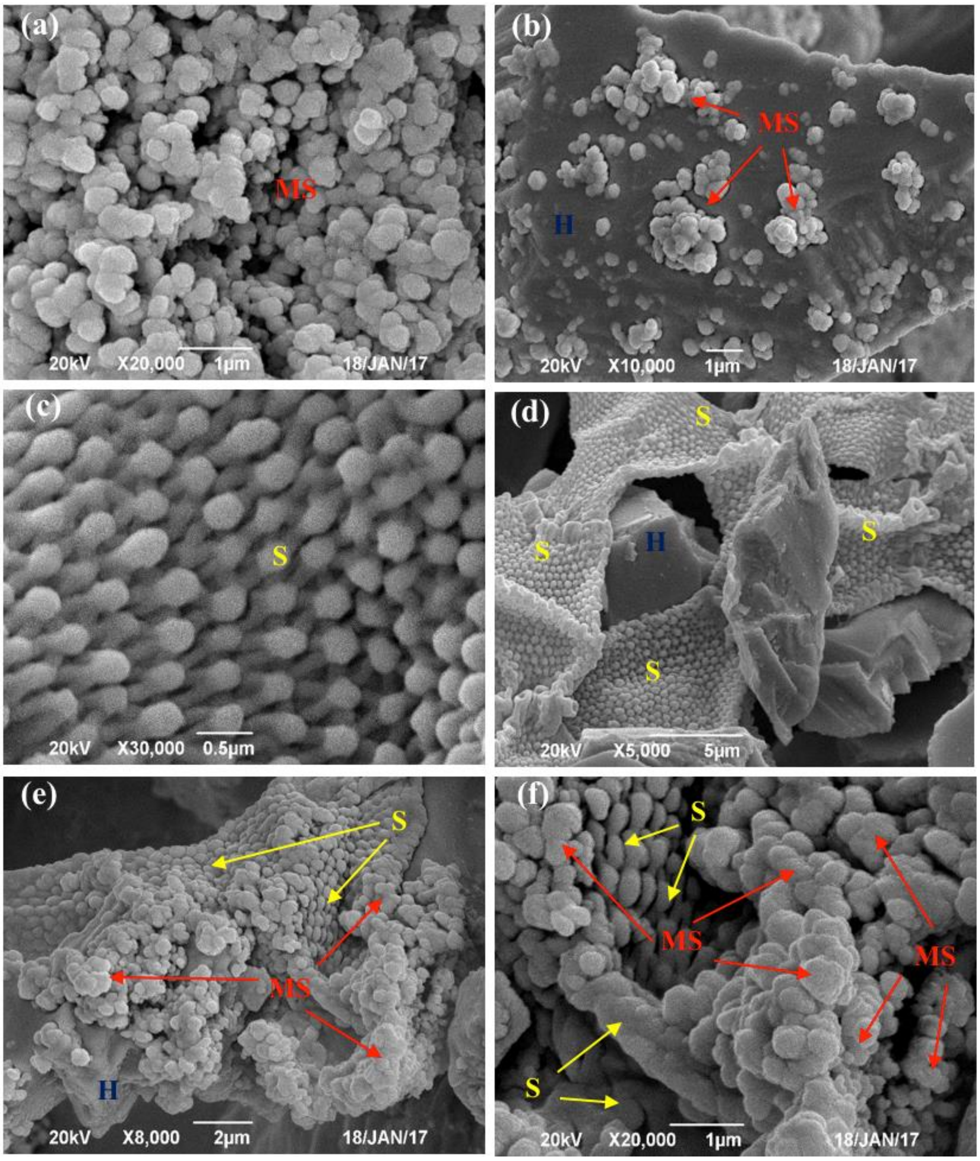

Fig. 11. SEM images of (a) magnetic seeds; (b) hematite coated with the magnetic seeds; (c) the crystalline caustic starch; (d) hematite coated with the caustic starch; (e & f) hematite coated with the magnetic seeds and caustic starch. MS: magnetic seed (100-200 nm), H: hematite, S: starch

4. Conclusions

The MSD was particularly beneficial to the reverse flotation of hematite ore slimes, exhibiting a good depressing ability on the target mineral hematite. The iron recovery increased with the increase of magnetic seeds, reaching the optimum Fe recovery 56.79% by using 180 g/Mg magnetic seeds. In addition, a moderate pre-magnetization intensity was also critical to the flotation depression.

Behind the increased depressing ability in the MSD there are two reasons: increased adsorption intensity of starch on hematite and the agglomeration of fine minerals. The starch adsorbed both onto the surfaces of hematite and magnetic seeds, thus acting as the bridging between hematite particles and magnetic seeds, resulting in an intensified coverage of the starch onto hematite and positive action in the agglomeration. The starch was absorbed onto the hematite prior to the magnetic seeds and the magnetic seeds are found outside the adsorption layer of the starch.

The magnetic interaction between magnetic seeds and hematite is characteristic of the long-range force. This long range magnetic force greatly enhanced the adsorption of magnetic seeds onto fine hematite and increased the magnetic susceptibility of hematite, and then helped the agglomeration of fine hematite in the presence of a low external magnetic field.

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