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WET HIGH INTENSITY MAGNETIC SEPARATION OF IRON MINERALS

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Abstract

Four different iron minerals were selected for study, and five size fractions of each mineral were prepared. The magnetic properties of these minerals were measured. The effect of particle size and magnetic susceptibility on wet high intensity magnetic separation was studied simultaneously. It was found that hematite–1 was a strongly paramagnetic mineral, and the effect of particle size in WHIMS was not significant. Goethite and limonite were weakly paramagnetic minerals, and could not be effectively recovered by WHIMS. The magnetic properties of hematite–2 were between hematite–1 and goethite and limonite, and the effect of particle size on WHIMS for hematite–2 was significant.

INTRODUCTION

In the practice of iron ore beneficiation, wet high intensity magnetic separation (WHIMS) has become a powerful technique for the recovery of fine, weakly magnetic iron minerals [1]. Many theoretical and experimental investigations into the fundamental principles of WHIMS have been reported [2 to 7], mainly concerned with a better understanding of the process of particle capture on a matrix. In most instances, the conclusions were concerned with the magnetic properties and configuration of matrix materials.

In a wet high intensity magnetic separator, magnetic separation is mainly based on a combination of magnetic force F_m, and hydrodynamic drag force F_d, acting on the particles. The force F_m can be given as following [8]:

$$F_m = \chi V_p (B_o \cdot \nabla B_o)/\mu_o$$

where χ is the magnetic susceptibility of particles with volume V_p, B_o is the applied magnetic field, ∇B_o is the magnetic field gradient, μ_o is the constant, $4\pi \times 10^{-3}$ H/m.

If we only consider particles of 200 micrometers diameter or less [8], the drag force F_d can be derived by the Stokes law expression:

$$F_d = 3\pi\eta d(u_p - u_o)$$

where η is the fluid viscosity, d is the particle diameter, u_p is the particle velocity and u_o is the fluid velocity.

Thus, variables affecting particle capture in WHIMS may be classified as design or equipment dependent and feed slurry dependent. In a given wet high intensity magnetic separator, the variables B_o, ∇B_o and u mainly depend on the magnetic properties and configuration of matrix. After configuration of the matrix has been determined, the performance of WHIMS will depend on the variables χ and d.

In the present work, the equipment variables were fixed and the effects of particle size and magnetic susceptibility were studied simultaneously. The aim was to observe the behaviour of iron minerals with different susceptibility and particle size in a given wet high intensity magnetic separator, and then to determine the particle size limit to the effective recovery of fine mineral particles. When particle size was less than this limit, a flocculation technique was adopted to facilitate recovery.

EXPERIMENTAL MATERIALS AND METHOD

In this study, four kinds of iron minerals were used: tow types of hematite (hematite–1 and hematite–2) with different magnetic susceptibility, goethite and limonite. These pure minerals were, respectively, wet ground by using a laboratory steel ball mill, and sized by a laboratory cyclosizer (Warman International (Pty), Ltd., Australia). Five size fractions of each mineral sample were obtained: –44+33, –33+23, –23+15, –15+11 and –11 μm.

The magnetic separation was conducted in a wet high intensity magnetic separator (bench model type BHW, made by Boxmag–Rapid Ltd., England). The matrix was a fine expánded stainless steel metal (about 1×4 mm), which was packed into the canister.

A feed slurry concentration of about 3% solid by weight was chosen. The sample weight of each test was less than 3 grams, ensuring that on the matrix surface there were enough spaces to attach magnetisable particles. The slurry was directly fed into the feed hopper at the same flowrate. To reduce the adverse influence of hydrodynamic force during the test process, the washing water was controlled carefully and the feeding rate was very slow (about 50 seconds).

Measurements of the magnetic properties of samples were carried out in a vibrating sample magnetometer Model 3001 (made by Oxford Instruments Ltd., England). The particle size of samples used was –11 μm.

EXPERIMENTAL RESULTS

Measurement of Magnetic Properties

According to magnetism theory [9], all materials can be classified into three types, that is, ferromagnetic, paramagnetic and diamagnetic materials. For paramagnetic and diamagnetic materials there is a simple linear relationship between the magnetisation and the applied magnetic field, but for ferromagnetic materials their behaviour is much more complicated.

If we use magnetic susceptibility to classify the materials, the susceptibility of paramagnetic materials is a small positive constant. For diamagnetic materials, the susceptibility is a very small negative constant, and for ferromagnetic materials it is variable and depends on the applied magnetic field and the previous history of the sample. For the four kinds of mineral samples tested, the relationship between the magnetisation and the applied magnetic field is shown in Fig. 1.

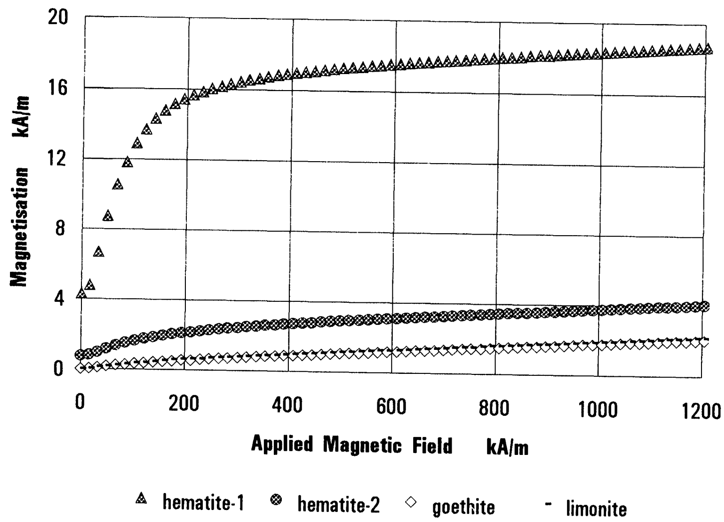

Fig. 1 Magnetisation curves of iron minerals

For hematite–2, goethite and limonite, the relationship between the magnetisation and the applied magnetic field was nearly linear. For hematite–1, when the applied magnetic field was less than about 400 kA/m, its behaviour was similar to a ferromagnetic material, and when the applied magnetic field was higher than about 400 kA/m, the behaviour was like a paramagnetic material.

The relationship between the volumetric magnetic susceptibility and the applied magnetic field is shown in Fig. 2. The order of susceptibility values of the four minerals was: hematite–1, hematite–2, limonite and then goethite. In the range of applied magnetic field from 0 to 1200 kA/m, the susceptibility of hematite–1 was not constant, but for limonite and goethite, the susceptibilities were nearly the same small positive constants.

From these results, it can be seen that hematite–1 is a strongly paramagnetic mineral with magnetic behaviour similar to ferromagnetic materials. Goethite and limonite are very weakly paramagnetic minerals.

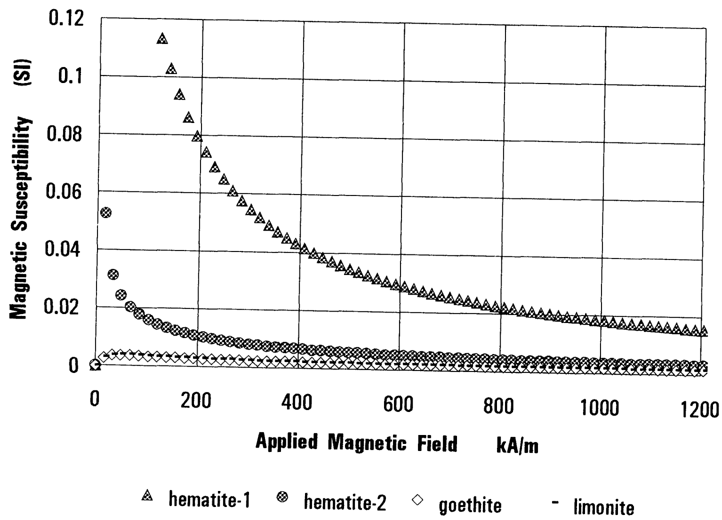

Fig. 2 Volumetric magnetic susceptibility curves of iron minerals

Magnetic Separation

Results of magnetic separation for hematite–1 are shown in Fig. 3. The recoveries of hematite–1 are all over 85%, and the particle size has a weak effect on the magnetic separation of hematite–1. If the magnetic induction is increased to over 0.7 Tesla, in the range of the test conditions, it seems that the particle size no longer affects the performance of magnetic separation.

For hematite–2, the results of magnetic separation are given in Fig. 4. Particle size has a significant effect on the magnetic separation of hematite–2. The hematite recovery decreases with particle size, and increases with magnetic induction. also, these relationships keep constant under all conditions tested.

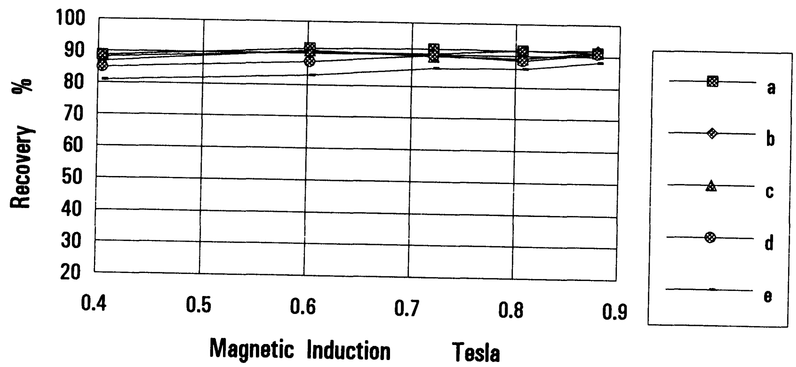

Fig. 3 Magnetic separation of hematite–1: (a) –44+33 μm, (b) –33+23 μm, (c) –23+15 μm, (d) –15+11 μm, (e) –11 μm

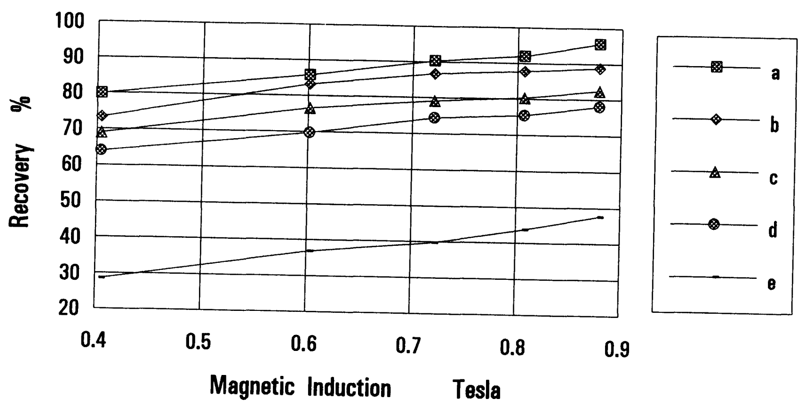

Fig. 4 Magnetic separation of hematite–2: (a) –44+33 μm, (b) –33+23 μm, (c) –23+15 μm, (d) –15+11 μm, (e) –11 μm

The results of of magnetic separation for goethite and limonite are, respectively, shown in Figures 5 and 6. In the range of particle size tested, the recoveries of goethite and limonite are all below 85%. Also, during the experimental process, it was found that the performance of magnetic separation is very sensitive to the feed flowrate. A small fluctuation of the rate would result in a remarkable change in recovery, and smaller the particle size, the more obvious the change was.

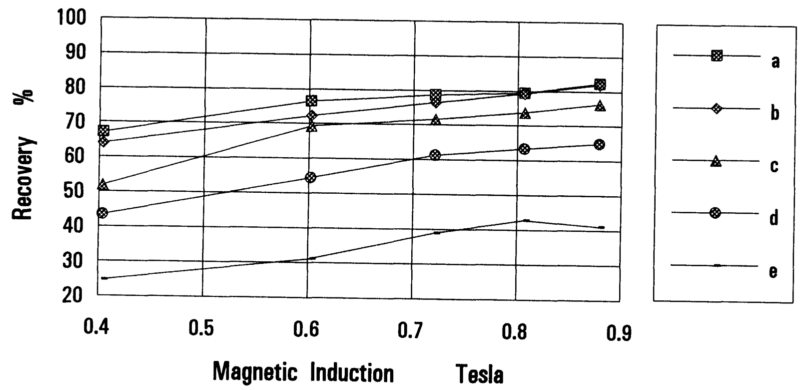

Fig. 5 Magnetic separation of goethite: (a) –44+33 μm, (b) –33+23 μm, (c) –23+15 μm, (d) –15+11 μm, (e) –11 μm

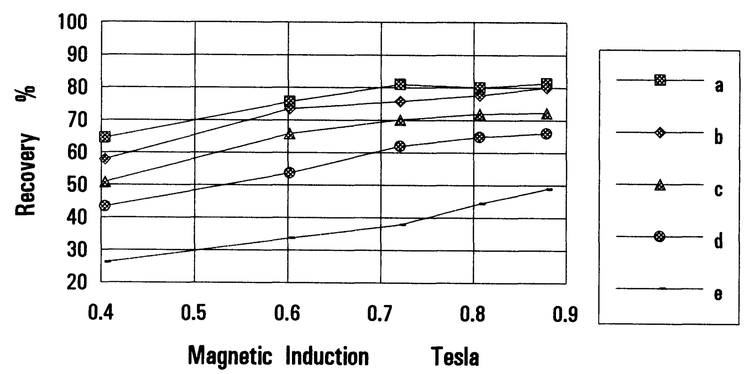

Fig. 6 Magnetic separation of limonite: (a) –44+33 μm, (b) –33+23 μm, (c) –23+15 μm, (d) –15+11 μm, (e) –11 μm

DISCUSSION

From magnetism theory [9], magnetic susceptibility is the dimensionless ratio between magnetisation M and magnetising field B. For paramagnetic materials, susceptibilities should be small positive constants. However, some minerals treated by WHIMS are not purely paramagnetic, but posses a certain degree of magnetic ordering which results in the field–dependence of their susceptibilities. Usually, magnetic susceptibility decreases with increasing applied magnetic field, and the drop in the value of magnetic susceptibility shows large differences amongst different minerals. The change in magnetic susceptibilities of the minerals tested is shown in Table 1.

Table 1 Volumetric magnetic susceptibilities of iron minerals

Mineral	Volumetric magnetic susceptibility (SI)				
	Magnetic induction (Tesla)				
	0.4	0.6	0.7	0.8	0.9
Hematite-1	$5.20x10^{-2}$	$3.59x10^{-2}$	$3.15x10^{-2}$	$2.74x10^{-2}$	$2.49x10^{-2}$
Hematite-2	$7.79x10^{-3}$	$5.93x10^{-3}$	$5.41x10^{-3}$	$4.89x10^{-3}$	$4.57x10^{-3}$
Goethite	$2.44x10^{-3}$	$2.15x10^{-3}$	$2.05x10^{-3}$	$1.97x10^{-3}$	$1.91x10^{-3}$
Limonite	$2.62x10^{-3}$	$2.33x10^{-3}$	$2.24x10^{-3}$	$2.12x10^{-3}$	$2.07x10^{-3}$

When the magnetic induction increases from 0.4 Tesla to 0.9 Tesla, the susceptibility of hematite–1 nearly decreases by over 50%. It indicates that hematite–1 possesses in a certain degree the behaviour of ferromagnetic materials, and for a given particle size of hematite–1, when the magnetic field of the magnetic separator increases, the change of magnetic force acting on hematite–1 mainly depends on the change of the magnetic field gradient.

From this Table it can also be seen that the susceptibilities of the other three kinds of iron minerals possess the same quantity order, 10^{-3} (SI), and goethite and limonite have similar values of magnetic susceptibility.

In practice, the wet high intensity magnetic separator is commonly used to treat iron ores containing many gangue minerals with diamagnetic properties. These gangue minerals often adversely affect the probability of collision between the magnetisable particles and the matrix surface, resulting in a decrease of recovery of iron minerals. Therefore, when determining the size limit of effective recovery by wet high intensity magnetic separation for pure iron minerals, a higher value should be selected. In this study, the recovery 85% was selected as a limit. For a given particle size of mineral, if the recovery of magnetic separation can be up to 85% in the range of magnetic field strength tested, this size can be defined as the size limit of effective recovery of this mineral.

From the results of the magnetic separation of four kinds of minerals, it can be seen that all the size fraction of hematite–1 can be recovered effectively by WHIMS. For hematite–2, only sizes greater than +23 μm can be directly treated by WHIMS, and this result is consistent wit the fact that the wet high intensity magnetic separator is in practice not suitable to treat iron ores of about –20 μm. For hematite–2 of –23 μm, therefore, a pre–treatment process,such as flocculation, would be required, in order to obtain an enhanced performance. Also, neither goethite not limonite can be effectively recovered by WHIMS, in all particle size ranges that were tested.

If we compare these results with the volumetric magnetic susceptibilities of minerals, it seems that when the susceptibility of minerals is larger than 2×10^{-2} (SI), the particle size would no longer affect the WHIMS performance. When the susceptibility is smaller than 2×10^{-3} (SI), iron minerals could not be effectively recovered by WHIMS. When the susceptibility is between 2×10^{-2} and 2×10^{-3} (SI), there is a significant effect of particle size on WHIMS of iron minerals.

CONCLUSIONS

Hematite–1 is a strongly paramagnetic mineral, and its behaviour is in some degree like a ferromagnetic material. In a wet high intensity magnetic separator, when magnetic field increases, the magnetic force acting on hematite–1 particles mainly depends on the increase of magnetic field gradient and there is no evidence of particle size affecting the magnetic separation of hematite–1.

Goethite and limonite are both weakly paramagnetic minerals. Both of them have similar values of volumetric magnetic susceptibility, about 2×10^{-3} (SI), and they cannot be effectively recovered by WHIMS in the particle size ranges tested.

The magnetic susceptibility of hematite–2 is between hematite–1 and goethite or limonite. Its susceptibility is about 4 to 7×10^{-3} (SI). The effect of particle size on the magnetic separation is significant. When a particle size is larger than 23 μm, hematite–2 can be effectively recovered by WHIMS, and when less than 23 μm, hematite–2 has to be pre–treated by flocculation or another process to improve the performance of magnetic separation.

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