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Electric arc furnace dust as magnetic carrier particles for removal of micro-fine particles from suspensions

Honghu Tang, Li Wang, Wei Sun *, Yuehua Hu, Haisheng Han, Jihua Zhai

School of Minerals Processing and Bioengineering, Central South University, Changsha 410083, China

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ABSTRACT

Electric arc furnace (EAF) dust, as a typical industrial waste, was often used as absorbents or building materials, which ignored its magnetic properties. In this study, EAF dust was first used as magnetic carrier particles to remove micro-fine particles from suspensions in hydrometallurgical processes. This dust was found to mainly consist of γ-Fe_2O_3 and 28.6% of it was below 900 nm. Even though in fine particle size, the EAF dust still showed an excellent settleability under the combined assistance of polyacrylamide and external magnetic field. As an application example, EAF dust magnetic flocculation process was employed to remove micro-fine particles from oxygen pressure acid leachate of vanadium bearing stone coal, which was difficult to separate. The results revealed a maximum suspended solids (SS) removal rate of 97.72% within 30 s. The SEM micrographs showed that SS particles either overlapped on the surface of coarse EAF dust or predominant agglomerated with fine EAF dust due to polymer bridging, forming large and compact SS-loaded magnetic floccules. The zeta potential analysis and DLVO theory calculations confirmed that the charge neutralization and mutual adsorption between micro-fine quartz and EAF dust. This study demonstrated that the EAF dust magnetic flocculation could efficiently remove micro-fine particles from suspensions, which may provide a cost-effective method for solid-liquid separation in hydrometallurgy.

1. Introduction

Electric arc furnace (EAF) dust, as an industrial waste, is generated in the electric arc steelmaking process, which is also a potential magnetic carrier for magnetic flocculation. During the meltdown of scrap, volatile components are fumed off and are collected with particulate matter in the off-gas cleaning system [1–3]. Therefore, EAF dust is very fine and major part of it is below 20 μm. Besides, it has almost the same magnetism as magnetite [3–6]. With original small particle size and large magnetic moment, this material is extremely suitable to be used as magnetic carrier particles for magnetic flocculation. However, most studies are focused on the use of EAF dust as an absorbent [7–10] or building materials [11–13] and seldom studies have concentrated on the application of the magnetic properties of EAF dust.

Magnetic flocculation has been turned out to be a promising method for the removal of magnetic solid particles and nonmagnetic suspended solids in wastewater [14–18] and hydrometallurgy [19–21]. The control of solid-liquid separation, especially the removal of suspended solids (SS) processes, is of primary importance in many vital industrial sectors including water and wastewater treatment, minerals processing, hydrometallurgy, paper manufacture, pharmaceuticals, and fine chemicals [22]. And sedimentation is one of the most widely used processes for separation of suspended solids from a liquid [23]. Flocculants, such as polyacrylamide (PAM) and its derivatives or copolymers, are widely employed as in the solid–liquid separation of suspended solids to promote rapid settling [24–29]. To improve the settling rate of suspended solids by flocculation, the magnetic separation was introduced into flocculation [30]. The removal of nonmagnetic suspended solids by magnetic separation relies on the use of the magnetic carrier technique to enhance the magnetic properties of solids to be removed. Separation of magnetic particles and floccules using magnetic separation is an effective way of significantly lowering the content of suspended solids in liquids, which have been adapted from ore mining industries to the anti-scale treatment of pipe lines [15,31–36].

Micro-fine particles such as gypsum and quartz, have caused serious problems in hydrometallurgy, especially for oxygen pressure acid leachate of vanadium bearing stone coal [37,38]. In China, the gross reserve of stone coal is 6.188 billion tons and 118 million tons of that is vanadium in the form of V_2O_5, accounting for more than 87% of the domestic reserve of vanadium. The extraction of

* Corresponding author.
E-mail address: sunmenghu@csu.edu.cn (W. Sun).

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vanadium from stone coal by oxygen pressure acid leaching was high energy consumption, resulting in obtaining a vanadium leachate with a V_2O_5 concentration of only 5–9 g/L and a H^+ concentration of nearly 1 mol/L [39,40]. However, the total suspended solids of this leachate were usually approximately 50,000 mg/L, which will severely affect the subsequent solvent extraction process. A conventional process to remove these SS was flocculating settling in a series of thickening tanks. And this procedure was time-consuming and large quantities of water washing would dilute the V_2O_5 concentration by 3–4 times. Besides, to improve the efficiency of flocculating settling, a lot of lime or limestone were used to neutralize the acid. These shortages were widespread in the process of removing suspended solid from strongly acidic solutions during metallurgical processing like vanadium bearing stone coal. Therefore, high efficiency and economical methods for removing suspended solids from leachate were imperative [41,42].

Magnetic flocculation would be a potential method of removing suspended solids from high solids content solutions including oxygen pressure acid leachate of vanadium bearing stone coal. However, the application of magnetic flocculation was uneconomical. In this procedure, magnetite is used as a magnetic carrier, which was found most useful [15,16,31,36,43]. Meanwhile, decreasing particle sizes of the magnetite used in magnetic separations from micrometers to nanometers would increase the available sorptive areas by 100 to 1000 times [44,45]. However, reducing the particle sizes of magnetite which has a high hardness, from micrometers to nanometers is a high energy-consuming process, which also needs special grinding equipment [46].

In this study, EAF dust was first used as a magnetic carrier in magnetic flocculation to remove SS such as micro-fine gypsum and quartz from the oxygen pressure acid leachate of vanadium bearing stone coal, which was an example of removing SS or solid/liquid separation from suspensions in hydrometallurgy. Firstly, EAF dust and SS in leachate were characterized by granulometric analysis, XRD, SEM and settleability analysis. Then the interaction mechanisms between EAF dust and SS particles were examined by zeta potential analysis and DLVO theory calculations. Finally, the cost and influences of EAF dust magnetic flocculation and conventional settling on the subsequent hydrometallurgical process were evaluated.

2. Materials and methods

2.1. Characterization of the samples and reagents

The vanadium bearing stone coal oxygen pressure acid leaching suspension in the experiments was obtained from Shanxi Province, China. The SS among the leachate was filtered and dried for analysis, abbreviated VSS. The electric arc furnace (EAF) dust and the magnetite mineral (Fe_3O_4) were supplied by Guangdong Shaoguan Iron & Steel Co., Ltd. (Baosteel Group) in China. The magnetite concentrate with a total iron content of 63.70% was obtained from Gansu Province, China.

All chemicals used in the experiments, such as polyacrylamide (Non-ion, 8–12 million molecular weight), sodium silicate and sodium hexametaphosphate (SHMP) were of AR/GR grades. Additionally, demineralized water was used throughout the experiments.

2.2. Chemical analysis

A Baird PS-6 ICP-AES (Inductively Coupled Plasma-Atomic Emission Spectrometry, Baird Company, USA) was used to determine the trace element compositions of the solutions. Elemental analysis of the solids was performed using X-ray fluorescence (XRF) spectrometry (PANalytical Axios mAX, Netherlands).

2.3. Granulometric analysis

The sintering dust size distribution was determined using a Malvern Mastersizer 2000 instrument (Malvern Instruments Ltd., Worcestershire, UK) with a detection range of 0.02–2000 μm. Scattered light is detected by a detector that converts the signal to a size distribution based on the volume. The variable D(0.5) is the diameter at which 50% of the measured particle volumes were less than or equal to D(0.5). Each sample was measured five times.

2.4. XRD analysis

X-ray powder diffraction data were collected on a D8 Advance automatic diffractometer in the Bragg-Brentano geometry and were used to evaluate the mineralogical composition of the treated and untreated suspended solids in the stone coal oxygen pressure acid leaching liquor, EAF dust and the magnetite concentrate. CuKa1 radiation (λ = 1.5406 Å) was used with a fixed counting time of 8 s in the $10° \leqslant 2\theta \leqslant 90°$ range with steps of 0.03° in 2θ. Standard procedures were applied to prepare the samples for analysis by X-ray diffraction [47].

2.5. Zeta potential measurement

The surface charge of the particles was assessed by zeta potential measurements using the Malvern zetasizer Nano ZS (Malvern Instruments, UK) at 25 °C and by applying a field strength of 20 V/cm. The zetasizer Nano measures the electrophoretic mobility of the particles, which were converted into the zeta potential using the Helmholtz–Smoluchowski equation built into the Malvern zetasizer software [48]. Samples were diluted in 10 mM KNO_3 as a background electrolyte. The mass fraction of solid particles in the original dispersion was about 1:5000. The strict control of the mass fraction is not crucial in measurements of zeta potentials by means of electrophoresis. The pH was adjusted by HCl solution before injection into the Malvern cell. For each new pH value, the samples were allowed to equilibrate for 5 min prior to data acquisition. All the measurements were performed in triplicate.

2.6. SEM investigation

Scanning electron microscopy (SEM) images and energy dispersive X-ray analysis (EDX) spectroscopy were taken on an FEI-quanta 200 scanning electron microscope (FEI Company, Hillsboro, OR, USA) using secondary electrons with an acceleration voltage of 20 kV. The samples were prepared by filtered the untreated and treated stone coal oxygen pressure acid leaching liquor. The surface of the samples were treated with a gold coating to improve the obtained images.

2.7. Total suspended solids and removal rate measurement

Total suspended solids (*TSS*) was measured by a filter. TSS values were calculated using the following equation.

$$TSS = \frac{(W_2 - W_1)}{V_s} \times 10^6 \tag{1}$$

In Eq. (1), *TSS* is the total suspended solids value (mg/L), W_2 is the weight of filter with residual (g), W_1 is the net weight of filter (g), and V_s is the volume of sample (mL) [49].

The suspended solids removal rate (*RR*) was calculated using the following equation.