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Multi-objective optimization of column flotation of an igneous phosphate ore

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In flotation process, the operating conditions under which the concentrate grade is high are the same conditions that lead to a lower recovery and selectivity. Thus, in the face of contradictory, but inherent characteristics of flotation phenomenon, it is necessary to apply appropriate techniques of multi-objective optimization in order to meet specific needs. In the present paper the Firefly Algorithm, associated with the Pareto dominance criterion and with an anti-stagnation operator, is used to determine the best operating conditions of the column flotation of an igneous apatite ore. The aim is to find the conditions that lead to a maximum P_2O_5 grade and recovery maximization, with adequate selectivity. The results indicated that the proposed approach was able to obtain the operating conditions which led to the best performances for this flotation process.

1. Introduction

The phosphate rock is a vital nonrenewable resource which is the only economically feasible source of phosphorus for phosphatic fertilizers and chemicals (Abouzeid, 2008). The progressive depletion of ore deposits under exploitation, allied to the growing demand for food in the world, makes it imperative to use phosphate deposits rationally (Vieira et al., 2010). Based on known reserves, the supply of phosphate rock of the earth may be exhausted in as little as 100 years if the demand continues to increase (Oliveira et al., 2011). Apatite of igneous carbonatite origin is the most important phosphorus source in Brazil, representing 80% of the Brazilian reserves (Arruda et al., 2009).

Froth flotation method has been an important part of the concentration process in phosphate industry. Inefficiencies in flotation translate into an enormous loss of revenue and an unnecessary waste of the reserves (Oliveira et al., 2011). Column flotation has received considerable attention and its use has become widespread because of its significant advantages over the conventional flotation cell, such as reduction of gangue entrainment in the froth, increase of bubble residence time in the pulp, and improved selectivity (Finch, 1995; Tao et al., 2000).

The primary objectives in flotation systems are recovery and concentrate grade. Selectivity is also an important variable because it affects the quality of the product and directly influences the subsequent flotation steps (Santana et al., 2011). However, these objectives may not converge to an ideal situation. In general, the operating conditions under which the P_2O_5 grade is high are the same conditions that lead to a lower P_2O_5 recovery (Santos et al., 2010). Thus, in the face of contradictory, but inherent characteristics of flotation phenomenon, it is necessary to apply appropriate techniques of optimization in order to meet the real and specific needs (Ghobadi et al., 2011).

In this context, the present study aims at determining the best operating conditions of column flotation of igneous apatite by the use of a multi-objective optimization technique that consists of P_2O_5 grade and recovery maximization, with adequate selectivity. For this purpose, the Firefly Algorithm, proposed by Yang (2008), associated to Pareto dominance concept is employed. The results obtained by this evolutionary strategy are compared with those obtained by the Weighted Sum Method (WSM).

2. Materials and experimental methodology

2.1. Material

The phosphate ore sample used in this work was supplied by the Vale Company from Barreiro carbonatite complex, located in Araxá, state of Minas Gerais, center-south of Brazil. The shape of the complex is roughly circular, with a diameter of 4.5 km and an area of approximately 16 km^2 (Lisboa et al., 2007). The host rocks consist mainly of carbonatites and glimmerites.

The weathering effects on glimmerite (with an essentially micaceous composition) caused partial alteration to vermiculite; other silicates were transformed into chlorite group minerals; iron minerals were altered and some of the apatite was changed to hydrated amorphous phosphates. The carbonatite suffered, beyond the above mentioned phenomena, leaching of carbonates and reprecipitation of iron, barium, phosphate and silicon ions (Guimarães et al., 2005).

In the Vale Company, the ore is processed in four physically distinct facilities: (1) crushing plant, (2) concentrator, (3) high field demagnetizing and filtration plant and (4) drying plant. The ore is

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crushed (jaw and impact crushers) and homogenized in the crushing plant and then it is reclaimed to the concentrator (Fortes et al., 2007).

The flotation section of the concentrator in the Vale Company, consists of six columns producing fine and coarse apatite concentrates. Barite is depressed with the other gangue minerals in the columns floating natural fines and fines from grinding (one column for each fraction). The coarse fraction circuit requires barite pre-flotation (one column), followed by apatite flotation (two columns in parallel); the tailings from these two columns are reground to improve the liberation of apatite, which is floated in the sixth column (Oliveira et al., 2011).

The material used in the present work came from the feeding stream of apatite flotation of the Vale Company. The chemical composition of this material was the following: 23.0% of P_2O_5, 16.2% of Fe_2O_3, 11.8% of SiO_2, 1.4% of $BaSO_4$, 29.2 of CaO and 1.0% of MgO.

2.2. Reagents and ore conditioning

In the early days of operation, all Brazilian plants utilized saponified imported tall oil as collector. Due to currency fluctuations and the low quality of local tall oil (high content of rosin acids), alternative collectors have now been adopted: rice bran oil, hydrogenated soybean oil, "sojuva" (a blend of soybean oil with oil extracted from grape seeds), rice bran oil blended with sulphosuccinate or sulphosuccinamate, and sarcosinate. The so-called oils are in fact a suite of fatty acids extracted from different vegetables (Santana et al., 2008).

Certain vegetables are capable of reacting self contained glycerol and fatty acid molecules producing triacylglycerol or oil molecules. Oil extracted from the vegetables is then purified and submitted to a process that combines heat, high pressure and alkalinity, being converted into fatty acids. The fatty acids are saponified with NaOH to produce soluble soaps that act as apatite collector (Guimarães et al., 2005).

Corn starch is the gangue depressant utilized in the flotation of igneous phosphate ores in all Brazilian concentrators. Depressants such as guar gum, tannins, ethyl cellulose, and carboxy methyl cellulose were widely investigated. The performance of corn starches was consistently superior to that of those reagents (Oliveira et al., 2007).

In the present work, a specific conditioning procedure was employed to turn hydrophobic surfaces of the apatite, using corn meal, rough rice oil, and sodium hydroxide. Starting with the corn meal, a macromolecular depressant was prepared through gelatinization, obtaining a solution of 3.0 wt.%. The used collector (rice oil) was saponified at a temperature of 70 °C, while stirring for 15 min. After that, the generated soaps were dispersed in water to obtain ready solutions with concentration of 2.5 wt.% oil. In all flotation tests and in the preparation of the reagents, process water from the processing plant was used. The conditioning procedure of the ore samples was performed at pH 11.5.

2.3. The experimental apparatus and test procedure

Fig. 1 shows a sketch of the experimental apparatus. The batch column, built in acrylic, has internal diameter of 40 mm and total height of 1.50 m. The air distributor utilized is made of sintered bronze. A foam washer is installed at the top of the column. Air and wash water flow rates are measured by means of flow meters.

In batch operation, the equipment operates with a circulating load which suspends the particles of the feeding and ensures the passage through the collection zone. The pulp is previously conditioned and then diluted to feed the batch flotation column from the top (15% of solid on the feeding), after adjusting the air flow rate and connecting the pulp recirculation device (0.5 L/min). The wash water is turned on and the floated material is collected until the froth is bare. The fraction that did not float is then drained from the equipment. The values of wash water and circulating load flow rate, unaltered during the tests, were 0.15 L/min and 0.5 L/min, respectively.

2.4. Chemical analysis and evaluation of the flotation products

The evaluation of chemical composition of the sample was done through X-ray fluorescence. The quality of the floated product was evaluated by means of the content and recovery of P_2O_5 in the flotation products. The recovery of each chemical specie (R) in the samples was calculated in agreement with Eqs. (1) and (2).

$$R_i = \frac{M_{Fi} x_{Fi}}{M_A x_A} \times 100 \tag{1}$$

$$R = \sum_{i=0}^{i=t_f} R_i. \tag{2}$$

2.5. Test program

In order to analyze the individual effects, as well as the interactions among the independent variables, a factorial experimental design of composed central orthogonal type was conducted (Box et al., 1978). The experimental programme was comprised of 16 tests with two

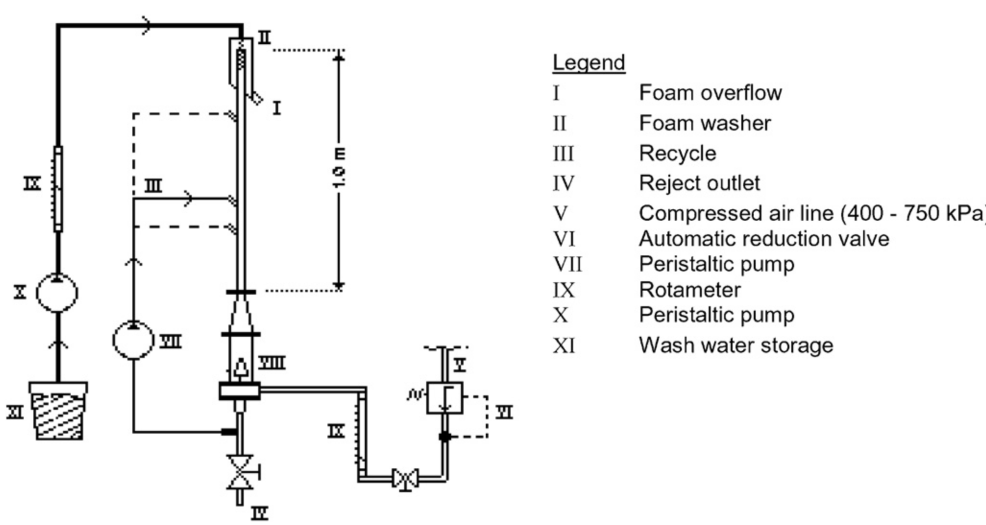

Fig. 1. Experimental apparatus.