Minerals Engineering 121 (2018) 129–136

Contents lists available at ScienceDirect

Minerals Engineering

journal homepage: www.elsevier.com/locate/mineng

Bench-scale insight into the amenability of case barren copper ores towards XRF-based bulk sorting

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ARTICLE INFO

Keywords:
Bulk sorting
Heterogeneity
X-ray fluorescence
Correlation
Sortability

ABSTRACT

XRF bulk sorting is put forward as a credible intender for pre-concentration methods in mining. This paper presents a preliminary study employing a bench-scale approach to calibrate XRF surface sensing to a target concentration of interest related to its volume so as to assess the feasibility of a case barren copper ore "slots" to bulk sorting. Firstly, various top sizes, along with different operators and specimens' weight/volumes, were examined to quantify the minimum readings needed (MRN) for XRF spot scanning at this scale. Multiple linear regression with a correlation coefficient of 0.921 was validated to be a reliable algorithm for calibrating XRF surface response to Cu volumetric concentration, owing to its consideration of elemental interacts. With the aid of graphical representations of calibrated data on recovery/grade curves, cut-off grade of 0.23% was chosen to enable 30% mass below the threshold to be discarded as waste and the remainder to go for further processing.

1. Introduction

It is generally recognized that comminution is an energy-intensive process. Estimations show that energy consumption for comminution accounts for approximately 75% of beneficiation operations (Tromans, 2008). Therefore, pre-concentration undoubtedly has massive potential to improve the profitability of hard rock mining (Salter and Wyatt, 1991) through the rejection of significant amounts of gangue in Run-of-Mine (ROM) ore ahead of comminution. Results indicate the application of ore sorting has substantial benefits in mining when pre-concentration is introduced during the very early stages of the mining cycle (Nayak et al., 2017), where sub-blocks below cut-off grade are unnecessarily processed, excavated or transported from open-pits or uplifted from underground mines.

For this purpose, one of the most beneficial developments in mining within the past 10 years was the development of high technology sensors to enable pre-concentration or sorting of mine ores (Veras et al., 2016), which includes charge-coupled device cameras (Pieper et al., 2016; Varela et al., 2006), X-ray transmission (Firsching et al., 2012; Lessard et al., 2014), near-infrared (NIR) sensing (Knapp et al., 2014), X-ray fluorescence (XRF) (West et al., 2015), radiometric sorting (Bowell et al., 2011), electromagnetic sensors (Bamber and Houlahan, 2010), eddy current detecting (García-Martín et al., 2011), and multi-sensor installation of two afore depicted (Kattentidt et al., 2003).

However, the typically available ore sorting technologies are particle sorting, i.e., rocks are positioned into a monolayer in order to be scanned individually, resulting in restricted throughput. Moreover, ore sorting is struggling with challenges such as common misconceptions about the actual impacts and benefits of ore sorting (Salter and Wyatt, 1991), shortage of mineral-specific sensor-based sorting systems in industrial scale, and unfavorable performance particularly in terms of results repeatability (Bamber and Houlahan, 2010).

One possible option of values determination with good repeatability may be sorting based on X-rays, which are described (Wikipedia, 2017) as electromagnetic radiation in the energy range of about 0.12–120 keV (wavelength range: of $10–10^{-2}$ nm). When materials are irritated by X-rays, electrons are ejected from the atomic shell, and the resulted free spots are occupied via an electron transfer from outer shells. This electron transition causes the emission of radiation (photons) – the so-called secondary X-ray fluorescence (XRF) radiation – and is characteristic for each transition and each element (Shackley, 2014), and the energies of emitted radiation correlate to the elemental composition (Weltje and Tjallingii, 2008). By measuring the photons radiation with individual detectors, ore sorting can be processed based on one

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https://doi.org/10.1016/j.mineng.2018.02.023
Received 14 December 2017; Received in revised form 16 February 2018; Accepted 23 February 2018
Available online 22 March 2018
0892-6875/

element, multiple elements or a ratio of two elements.

In the infancy of XRF-based sorting, only homogenous waste streams were treated. Currently, XRF is acquiring its reputation in heterogeneous materials sorting (West et al., 2009), such as diamond (Gaft et al., 2015), precious metals, base metals, ferrous and non-ferrous metals (Mohanan et al., 2013), and low phosphorous iron ores (Kruukka and Broicher, 2002). However, there are few reports regarding bulk sorting of barren copper ores.

To this end, this manuscript highlights the benefits of effective and higher capacity bulk sorting technique, available for segregating the "rich-ore" from waste and shrinking the volume processed downstream. X-ray fluorescent (XRF) was chosen for sensing low-grade copper ores owing to its quantitative response to elements in question.

To the application of XRF based sorting, matrix effects on XRF digitized response should be taken into consideration. The intensity of XRF radiation is a complex function of device factors, matrix composition (Sitko, 2008), sample thickness (Verma, 2007), and particle size (Finkel'shtein and Gunicheva, 2008; Maruyama et al., 2008). Ma and Kim (2008) discovered that XRF analysis of multi particles was different from that of separate grains. Therefore, matrix effects cannot be neglected and should be calibrated for quantitative analysis.

One of the issues affecting bulk sorting XRF based is the reliability of surface sensing. In other words, whether the XRF surface sensing can be convergent, and whether the measurement of surface characteristics is sufficient to directly represent the object's volumetric distribution or indirectly represent it under a suitable correlation. As for the correlation, a single rule cannot be adopted in every case due to mineralogical diversities of different deposits (Klein et al., 2002). Therefore it is highly recommended to perform a customized correlation for surface measuring.

Another issue determining bulk sorting is the ores' inherent characteristics. According to Esbensen and Wagner (2014), process streams, lots and materials in general that are significantly heterogeneous are so both concerning compositional (CH) and distributional heterogeneity (DH). Higher DH is ideal for bulk sorting (Esbensen and Wagner, 2015a, b). Thus, to undergo a preliminary study on XRF based bulk sorting, it is necessary to artificially create a series of copper ore "lots" with a relative higher DH, so that the sortability evaluation is meaningful for systematically delineating the bulk sorting process of low-grade ores before the beneficiation process.

As explained above, this study firstly concentrated on the identification and quantification of adequate spot scanning times needed for XRF surface sensing, at different size distribution (top size), different operators and sample weights (volumes). Secondly, a bench-scale method, including artificially creating a set of copper ore lots with an intrinsic heterogeneity, was proposed to evaluate the amenability of barren copper ores towards XRF-based bulk sorting. Next, the calibration of XRF readings on the interest at the surface to elemental contents in the volume was performed. Finally, using the calibrated data, the feasibility of ores in question to XRF based bulk sorting was evaluated and scaled.

2. Materials and methodology

A series of bench-scale tests taking advantage of XRF were carried out on samples of low-grade copper ores from Copper Mountain mine in Canada. The as-sampled ores were screened into five size fractions ranging from 0 mm to 37.5 mm. The XRF tests were performed on various top sizes, different operators, and total weights to determine the minimum spots readings needed (MRN). Next, case barren copper ore "lots" were artificially created, comprising 78 "groups" with the same weight (± 5%) but different levels of value, i.e., with a specific heterogeneity. The XRF surface readings of every "group" were correlated to volumetric Cu concentration. Based on the calibrated data, feasibility to bulk sorting was evaluated. Materials and methodology are elaborated hereinafter.

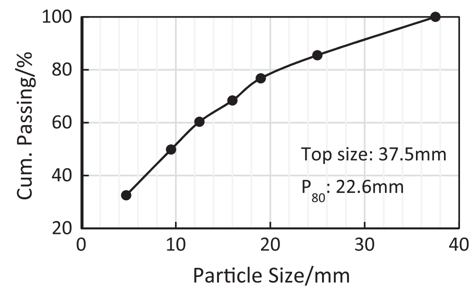

Fig. 1. Particle size distribution of as-sampled ores. This −37.5 mm sample with P_{80} 22.6 mm was further partitioned into 5 size fractions (−37.5 + 25, −25 + 16, −16 + 9.5, −9.5 + 4.75 and −4.75 mm) for XRF scanning.

2.1. Materials and equipment

Low-grade copper ores approximately 400 kg from SAG belt were sampled from Copper Mountain mine in Canada, and its particle size distribution is shown in Fig. 1.

2.2. XRF test settings

In this present work, XRF tests were carried out with the aid of Innov-Xsystms α-6000 (INNOV-X SYSTEMS IN., WOBURN, MA) shown in Fig. 2. Soil mode was employed with leap settings of sequential and combining test results. For each specimen, 50 random spots were scanned first for 5 s on standard element test, and then for 5 s on light element test. Since the XRF beam was equipped beneath the specimen platform, a micro area (typically diameter of 0.5 mm) (Shaffer and Bonvin, 2014) at sample bottom was scanned at a time. Subsequently, the XRF sensings were digitalized, transferred to a screened smartphone and stored as XRF readings, which could be exported in the form of an Excel spreadsheet, showing the component elements and their contents. Ahead of each specimens test, standardization with a circular slice of calibrator was conducted.

2.3. Minimum readings needed (MRN)

For each specimen, the 50 readings of the wanted Cu were compiled and averaged sequentially from the first one, the first two, the first three,… up to all the 50 readings. Percentage difference, defined as the difference between the average values of a reading alignment versus the last one within the alignment, was introduced to assess the averages'

Fig. 2. XRF setup used in tests.