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Rapid gangue mineral concentration measurement over conveyors by NIR reflectance spectroscopy

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A R T I C L E I N F O

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A B S T R A C T

Near-infrared (NIR) reflectance spectroscopy is being used increasingly as a laboratory technique to supplement XRD analysis and other measurements of blast-hole cuttings for metallurgical processing decision making. The advantage of the technique is the speed of measurement and the lack of need for sample preparation. NIR is a surface measurement that responds to transition element, electronic transitions and molecular, vibrational transitions in crystal lattices. The constituents of a sample are quantified by creating predictive models by regression against primary sample analyses through XRD, XRF and CEC.

We have developed predictive models for concentrations of swelling clays, kaolinite, muscovite and biotite from conveyor samples of copper ore using a QS 8000 over-the-conveyor system. The results are precise enough to be used for real-time, process decision making. In addition, prediction models have also been developed for seven oxides in limestone conveyed to stockpiles in cement plants.

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1. Introduction

As in any manufacturing or processing industry there is a constant need to improve efficiency and the quality of the product, and metallurgical processing is no exception. Measuring the concentration of swelling clays in the feedstock is crucial to the success of heap leaching. Knowing the buffering qualities of ore material bears on the amount of acid required in the agglomeration process. A mineral such as talc, a problem for the flotation process, is readily detected by reflectance spectroscopy. Continuous measurement of these properties and others is now feasible with new near-infrared (NIR) systems mounted over-the-conveyor belt.

Reflectance spectroscopy measurements from afar have a long history dating back to measurements of lunar and planetary surfaces through telescopes and were qualitative in nature. By adopting a data analysis technique from the analytical chemistry field, known as chemometrics, it is possible to build predictive models and quantify mineral concentrations. New illumination and spectrometer systems now exist to make over-the-conveyor (OTC) measurement in difficult environments. We present results for mineral concentrations in copper ores and oxide contents in limestone used in cement production.

2. Background

All that was known about the composition of the lunar surface before the first soft landing by a Surveyor spacecraft in 1966 came from telescopic spectral reflectance and emission measurements, and the choice of landing sites for the Apollo missions was based to a large extent on the same measurements (Goetz and Soderblom, 1969). Much of what we know currently about planetary surfaces is based on remote sensing spectral measurements from spacecraft (Pieters and Englert, 1997). Remote sensing of the Earth for geologic and environmental mapping has relied on quantitative spectral measurements of reflected sunlight since the launch of Landsat-1 in 1972 and continues to this day (Goetz and Rowan, 1981).

NIR spectroscopy has been successfully applied to a wide range geologic problems including: mineralogical mapping the lunar surface (McCord and Adams, 1973); mineral exploration (Goetz et al., 1983); airborne and spaceborne mapping of hydrothermal alteration (Kruse et al., 2003); mineralogical analysis of drill cores (Kruse, 1996); field mapping of expansive soils (Chabrillat et al., 2002); and field mapping of mineral assemblages for gold deposit exploration (Bierwirth et al., 2002). The use of chemometrics to quantitatively relate measured NIR spectra to properties of interest has allowed for the use of NIR spectroscopy for a wider range of applications, for example field determination of soil swell potential (Goetz et al., 2001) and soil nutrient analysis (Shepherd and Walsh, 2002).

The spectrum acquisition technology, embodied in a portable spectrometer system, the ASD TerraSpec, is in use by more than 100 companies for mineral assemblage mapping and drill core analysis in support of precious metal deposit exploration. In addition to alteration assemblage mapping, detailed spectral analysis allows for determination of minor compositional and crystallinity differences in minerals such as pyroxenes (Fig. 1), illites (Fig. 3)

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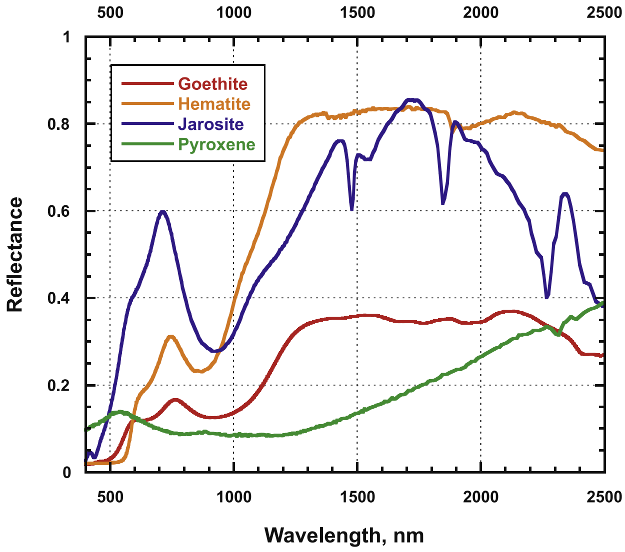

Fig. 1. Reflectance spectra of four iron minerals (after http://speclab.cr.usgs.gov/).

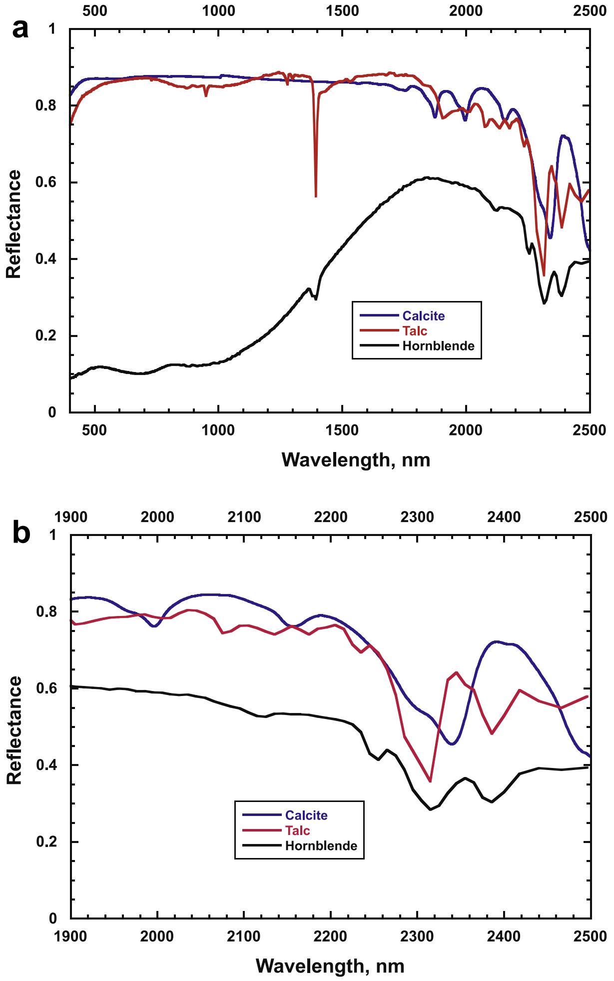

Fig. 2. (a) Spectra of calcium carbonate and Mg and Fe bearing silicates containing OH groups and (b) expanded wavelength scale (after http://speclab.cr.usgs.gov/).

and chlorites (Yang et al., 2000). In many cases, these differences can be used for geothermometry (Arkai et al., 1995).

The physics of reflectance spectroscopy for geologic materials is the same whether applied to planetary surfaces or for rock moving on a conveyor belt. Here we discuss results of spectrum acquisition with an ASD QS 8000 OTC system that covers the wavelength range 400–2500 nm, also known as the visible–NIR range, situated 1.6 m above the sample. The shape of the spectra and the positions of absorption features are determined by electronic and vibrational processes in mineral lattices and are also a function of particle size (Hunt and Salisbury, 1970; Pieters and Englert, 1997).

There are several kinds of electronic processes; crystal field effects, charge transfer, color centers and conduction band transitions. The first two are of the most relevance to the mineral processing applications discussed here. When a photon from a light source strikes a material, the resulting first surface reflection can be described by classical physics through Maxwell's equations. However, some of the light enters the material and its fate is subject to quantum mechanical rules, which determine how the material will react to light of various wavelengths. The photon has an energy $E = h\nu$ where ν is the frequency and h is Planck's constant. The equation can also be written as $E = hc/\lambda$ where c is the velocity of light and λ is the wavelength. Wavelengths are absorbed at transitions from one energy state to another. In transition elements such as iron, the unfilled 3d orbitals have degenerate energy levels, but when located in a mineral lattice the energy levels are split by interaction with the crystal field giving rise to spectral absorption features that depend on the valence state and the type of lattice. Therefore, the same transition element ion can give rise to different spectral features depending on the mineral. An example of these differences can be seen in Fig. 1.

The energy transitions for the Fe^{3+} minerals hematite, goethite and jarosite have absorption minima at approximately 870, 910 and 920 nm respectively. The Fe^{2+} mineral pyroxene has absorption near 1000 nm.

Charge transfer bands arise when absorbed energy precipitates an electron to move between ions. For instance, in hematite the charge transfer is between iron and oxygen causing a very strong absorption feature in the UV region and the effects are seen in the visible region as a drop off in reflectance toward shorter wavelengths (Hunt, 1977; Goetz, 1989; Pieters and Englert, 1997).

The atoms in a crystal lattice are bound together by electrical forces that act like springs. A photon with the proper energy and, therefore, resonant frequency will cause the atoms to vibrate, creating physical displacements of the atoms. There are $3N-6$ fundamental vibrations possible in a three-dimensional crystal lattice where N equals the number of atoms. Calcium carbonate, for instance, has five atoms in a unit cell. Therefore, there are nine fundamental frequencies that will cause absorption features in a reflectance spectrum. These absorptions are all in the mid-IR portion of the spectrum. However, there are also allowed overtones and combinations of the fundamental frequencies that can appear at higher frequencies (shorter wavelengths) of the NIR. A combination feature for calcite can be found at approximately 2350 nm in Fig. 2. When Mg substitutes for Ca in the solid solution series, the absorption feature shifts to shorter wavelengths. This shift can be used to determine the degree of dolomitization of limestone.

The features in talc and hornblende are a combination of the Mg–OH bending mode and the OH stretch, both of which are at longer wavelengths than recorded in the NIR.

The clays shown in Fig. 3 exhibit combination bands of Al–OH and OH. Kaolinite $[Al_4(Si_4O_{10})(OH)_8]$ can be separated from illite and smectites because of a prominent doublet caused by slightly different sites where the OH groups are located. These differences were exploited by Goetz et al. (2006) to develop a technique for the identification of swell potential in soils at construction sites.

In muscovite, a dioctrahedral phyllosilicate, the OH groups are coordinated around aluminum and exhibit an absorption band at approximately 2200 nm. In biotite the OH groups are coordinated

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