



Effect of microwave pre-treatment on ultramafic nickel ore slurry rheology



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ABSTRACT

Low-grade ultramafic nickel ores, while representing a large potential nickel resource, are difficult to process due to their high serpentine content. Serpentine is anisotropic and the mineral particles tend to be non-spherical, resulting in challenging slurry rheology. In general, suspensions of serpentine minerals have high viscosity and yield stress, which can be detrimental in comminution and flotation operations. It is proposed that ultramafic nickel ores be treated with microwave radiation prior to grinding in order to reduce slurry viscosity and yield stress. The rheology of two different ultramafic nickel ores, before and after microwave pre-treatment, was characterized in this work. Serpentine minerals were found to dominate the rheology of the untreated ultramafic nickel ores, with the ore containing minor chrysotile exhibiting higher viscosity and yield stress than the ore containing strictly lizardite serpentine. Microwave pre-treatment was found to greatly reduce the shear viscosity (average 80% reduction at 200 s^{-1}) and direct yield stress (peak yield stress reduced by 92–93%) of ultramafic nickel ore slurries. The reduction in slurry viscosity and yield stress of the ore slurries as a result of microwave pre-treatment was attributed to the conversion of serpentine to olivine.

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1. Introduction

Interest in low-grade ultramafic nickel ores has increased in recent years as traditional high-grade nickel sulphide deposits are being depleted and laterite ores have proven technically difficult and costly to process (Xu et al., 2010). While ultramafic ores represent a large potential nickel resource, they are challenging to process due to their high serpentine content (Senior and Thomas, 2005; Uddin et al., 2012). Serpentine is a phyllosilicate mineral comprised of 1:1 stacked sheets of silica tetrahedra and magnesium hydroxide octahedra, with adjacent sheets held together by weak van der Waals forces (Alexander et al., 2007; Alvarez-Silva et al., 2010). There are three primary polymorphs of serpentine: lizardite (platy), antigorite (corrugated) and chrysotile (coiled, fibrous) (McKelvy et al., 2004).

Serpentine minerals are anisotropic and have three different surfaces that can be exposed in solution (Fig. 1), each with a different surface chemistry. The basal planes of both the tetrahedral and octahedral sheets are electrically neutral upon crystal cleavage; however, pH-independent charging can develop through lattice

defects (vacancies or substitutions) (Alvarez-Silva et al., 2010). The edge surfaces, in contrast, are highly polar due to the breakage of bonds and pH-dependent charging occurs in solution through hydrolysis (Alvarez-Silva et al., 2010; Yan et al., 2013). The anisotropic nature of serpentine leads to complex rheology, which is compounded by the non-spherical shape of serpentine particles (Ndlovu et al., 2013). Suspensions of serpentine minerals, especially those of the fibrous chrysotile, are known to exhibit high viscosity and yield stress (Ndlovu et al., 2011).

In mineral processing, high pulp viscosity and yield stress can be detrimental to comminution and flotation. The presence of serpentine minerals in ores has been shown to reduce grinding efficiency, necessitating that grinding be conducted at lower densities (Ndlovu et al., 2014; Patra et al., 2010; Xu et al., 2010). With regard to flotation, high slurry viscosity results in reduced gas dispersion and mixing efficiency, cavern formation, increased turbulence damping, bubble coalescence and high gangue recovery (Becker et al., 2013; Cruz et al., 2013; Ndlovu et al., 2013; Todd, 2004; Shabalala et al., 2011). The flotation performance of ultramafic nickel ores is poor without some kind of serpentine neutralization or removal strategy (Senior and Thomas, 2005; Xu et al., 2010). Methods employed to improve the flotation of ultramafic nickel ores include desliming by cyclones (Senior and Thomas, 2005; Xu et al., 2011), the addition of chemicals such as

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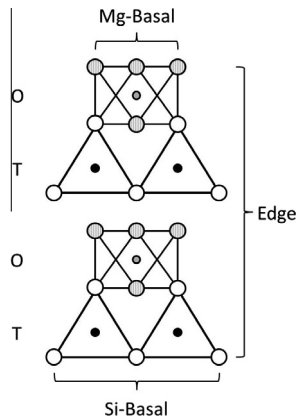


Fig. 1. Diagram showing serpentine structure and surfaces. T indicates a tetrahedral layer, O indicates an octahedral layer, a white circle indicates an oxygen atom, a black circle indicates a silicon atom, a grey circle indicates a magnesium atom, and a striped circle indicates a hydroxyl group.

carboxymethylcellulose or salts (Senior and Thomas, 2005; Peng and Seaman, 2011), and acid treatment of the flotation pulp (Uddin et al., 2012). Each of these strategies is focused on removing or deactivating serpentine.

A new method of reducing the viscosity and yield stress of ultramafic nickel ore slurries is proposed: microwave pre-treatment. Microwave radiation is electromagnetic radiation with frequencies of 0.3–300 GHz and wavelengths of 0.001–1 m (Haque, 1999). Microwaves have been used in a number of extractive metallurgical applications, such as for enhancing comminution (Amankwah and Ofori-Sarpong, 2011; Henda et al., 2005; Kingman et al., 2004; Walkiewicz et al., 1991) and leaching (Al-Harrahshah and Kingman, 2004, 2008; Schmuhl et al., 2011; Zhai et al., 2010), as well as for drying, calcining and smelting operations (Haque, 1999; Kingman and Rowson, 1998; Pickles, 2009). Microwaves, however, have not been used before for the modification of pulp rheology.

Upon exposure to microwave radiation, ultramafic nickel ores are heated, resulting in the dehydroxylation of serpentine and the formation of olivine (Eq. (1)) (Bobicki et al., 2014).



Olivine is a mineral composed of isolated SiO_4 tetrahedra linked by octahedrally coordinated magnesium ions (Alexander et al., 2007). Olivine is isotropic, non-fibrous, and is not reported to have complex rheology or cause problems in ultramafic nickel ore processing. The objectives of this work were (1) to study the rheology of two ultramafic nickel ores, one containing chrysotile and one containing only lizardite serpentine, (2) to determine if microwave pre-treatment can be used to improve the rheology of ultramafic nickel ores, and (3) to explain the mechanisms behind any rheological changes that occur in ultramafic nickel ores as a result of microwave pre-treatment.

2. Materials and methods

2.1. Mineral feedstock

Two different ultramafic nickel ores were studied. The first ore was from the Okanogan nickel deposit in Washington State, USA (referred to as “OK ore”). The second was from the Vale-owned Pipe deposit located in the Thomson Nickel Belt (referred to as “Pipe ore”). The ores were crushed and sieved to isolate the 0.425–1 mm size fraction for microwave pre-treatment. The mineral composition of the OK and Pipe ores before and after

microwave pre-treatment is shown in Table 1 (Bobicki et al., 2014). The serpentine present in the OK ore is of the lizardite form. The serpentine in the Pipe ore is primarily lizardite with approximately 1 wt.% chrysotile. Since chrysotile and lizardite are difficult to distinguish by XRD, the chrysotile content of the Pipe ore (fibres of which are visible to the naked eye) was determined by Mineral Services Canada in a report to Vale Ltd. using a combination of XRD, petrography and SEM techniques (Mineral Services Canada, 2009; Xu et al., 2010). Heat capacity and dielectric data for individual minerals found within the ores are shown in Fig. 2.

2.2. Microwave treatment

A 1000 W, 2.45 GHz, multimodal household microwave oven (Panasonic NN-SF550M Flat and Wide) was used to conduct microwave treatment. 100 g ore samples were placed in 100 mL quartz crucibles, which were then placed in the microwave reactor for treatment. Ore was treated at full power (1000 W) for the full microwave treatment time and the microwave reactor was purged continuously with 1 L/min of nitrogen gas both during microwave treatment and cooling of the samples. The OK ore was exposed to microwave radiation for 15 min, during which time the ore reached a temperature of 730 °C. 15 min microwave treatment was selected for the OK ore as this treatment time resulted in maximum heating. Further treatment did not result in further heating. The Pipe ore was exposed to microwave radiation for 8 min, during which time a temperature of 686 °C was achieved. The Pipe ore was only exposed to microwave radiation for 8 min because any further treatment caused the Pipe ore to melt. The ores were found to heat better in response to microwave radiation than pure serpentine due to the presence of highly microwave responsive minerals, such as magnetite (Bobicki et al., 2014). A detailed explanation of the heating characteristics of the ores and the mineralogical changes that occur as a result of microwave pre-treatment are given in Bobicki et al. (2014).

2.3. Grinding

100 g samples of untreated and microwave pre-treated OK and Pipe ore (0.425–1 mm size fraction) were ground aqueously in a stirred attrition mill (01-HD Laboratory Attritor with 1400 cc tank, Union Process, Akron, Ohio, USA). Grinding was conducted at 1000 rpm using 1300 g (560 mL) of 99.5% 3/16” alumina balls (Union Process, Akron, Ohio, USA) and 250 mL of 10^{-2} M KCl. Each sample was ground to a P_{90} of $8.5 \pm 0.2 \mu\text{m}$.

Table 1

Mineral composition of OK and Pipe ores before (OK UT and Pipe UT) and after (OK MW and Pipe MW) microwave pre-treatment from quantitative XRD analysis (Bobicki et al., 2014).

Mineral	Formula	OK UT	OK MW	Pipe UT	Pipe MW
Serpentine (wt.%)	$\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$	84.0	15.8	63.7	23.7
Olivine (wt.%)	Mg_2SiO_4	–	80.2	7.7	51.1
Cordierite (wt.%)	$\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$	–	–	1.0	1.0
Vermiculite (wt.%)	$\text{Mg}_2\text{Si}_4\text{O}_{10}(\text{OH})_2$	–	–	0.7	–
Brucite (wt.%)	$\text{Mg}(\text{OH})_2$	5.1	–	–	–
Dolomite (wt.%)	$\text{CaMg}(\text{CO}_3)_2$	–	–	5.5	1.4
Magnetite (wt.%)	Fe_3O_4	6.6	4.0	12.3	14.1
Pyrrhotite (wt.%)	$\text{Fe}_{(1-x)}\text{S}$	–	–	4.7	5.6
Pentlandite (wt.%)	$(\text{Fe}, \text{Ni})_9\text{S}_8$	4.3	–	2.8	0.8
Quartz (wt.%)	SiO_2	–	–	1.6	2.3

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