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Economic analysis on the application of mechanical activation in an integrated mineral carbonation process

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ABSTRACT

This paper investigates the feasibility of mechanical activation as a pre-treatment method as part of an integrated mineral carbonation process for a nickel mining operation in British Columbia. The physical, structural and chemical characteristics of forsterite and lizardite in mine waste rock after mechanical activation were monitored to determine their CO_2 sequestration efficiency for a direct aqueous carbonation process. Economic analysis on the process was developed through considering the energy requirements, cost modeling and carbon balance. Mechanical activation on mining residue reduced the particle size, enlarged the surface area, distorted the crystal structure of forsterite, and enhanced the CO_2 sequestration efficiency. However, it didn't create new phase or induce phase transfer between forsterite and lizardite, and distort the crystal lattice of lizardite. The optimum condition for 60% CO_2 sequestration efficiency was found at mechanical activation for 210 kWh t^{-1} ore and carbonation for 260 kWh t^{-1} ore, which had an operating cost of 104.1–107.1 \$ t^{-1} CO_2 avoided. Using mechanical activation, the integrated mineral carbonation plant in the mine can potentially sequester 14.62 Mt y^{-1} CO_2 using mine waste rock and tailings during the 28-year life of mine.

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1. Introduction

Anthropogenic greenhouse gas (GHG) emission since the pre-industrial era has widespread impacts on the natural systems (Valentin, 1993; Zadrazil and Puniya, 1994) and leads to climate change (IPCC, 2014). Carbon dioxide (CO_2) is a type of GHG (Chen et al., 2013). The CO_2 emission is about 70% of total GHG emissions annually, which is much larger than other GHG variations, such as methane (CH_4) and nitrous oxide (N_2O) (IPCC, 2014). Substantial and sustained reduction in CO_2 emissions is urgently required.

Mineral carbonation (MC) is part of natural silicates weathering process which occurs on a geological time frame (Ascaso et al., 1998; Bordenave et al., 2013; Daskalakis et al., 2015; Favero-Longo et al., 2013, 2006; Garcia-Vallès et al., 2000; Herrera et al., 2004; Prieto et al., 1997; Yin et al., 2014). In the process, CO_2 dissolved in rain water, and react with magnesium or calcium bearing rocks to form carbonate rocks. Due to the formation of stable carbonates, MC is recognized as the only way that could permanent store CO_2. Over the past decades, CO_2 sequestration by MC has been evolved and rigorously pursued globally through developing various carbonation routes and conditions, as well as pre-treatment methods for feedstock, aims at accelerating the process for large scale implementation (Power et al., 2013). Until recently, only a few MC technologies have achieved the commercial stage. The high cost of MC (50–300 \$ t^{-1} CO_2) limits their application (Sanna et al., 2014). The cost of carbonation can be reduced through various methods, such as using waste materials as CO_2 feedstock (Bobicki et al., 2012; Bodor et al., 2013), sequester CO_2 from flue gas directly (Pasquier et al., 2014), producing valuable carbon products (Hemmati et al., 2014), or integrating MC into a suitable industry plant, such as ultramafic rock hosted mining deposit (Hindle, 2011).

Integrating MC into hard metal mining industry has been addressed to be an energy efficient way and sustainable growth method towards reducing its contribution to CO_2 emissions (Ballantyne, 2010). The suitable mining plants are usually open pit mine deposits that hosted by ultramafic or mafic rocks, such as nickel, diamond, chromite, and platinum group elements (PGE) mines (Hitch et al., 2010). Mining activities in these mines generate a great quantity of waste materials (i.e. waste rock, tailings, and slag), which are mainly composed of Mg- and Ca- bearing silicates

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Nomenclature

B_0	the background of the diffraction peak for a non-activated mineral
B_x	the background of the diffraction peak for the mechanically activated mineral
C_{XRD}	crystallinity (%)
$CO_{2,\ sequestrated}$	the annual CO_2 sequestrated (ty^{-1})
$CO_{2,\ avoided}$	the annual CO_2 avoided (ty^{-1})
$CO_{2,\ emitted}$	the annual CO_2 emitted (ty^{-1})
D_V	crystallite size
d_{80}	particle size of 80% passing (μm)
E_{power}	the amount of power used in the carbonation process (kWh)
ε_{power}	the amount of CO_2 produced when generating the necessary amount of power (kg CO_2 $kW^{-1}h^{-1}$)
E_C	energy consumption of mineral carbonation ($kWht^{-1}$)
E_M	energy consumption of mechanical activation ($kWht^{-1}$)
I_0	the integral intensity of a diffraction peak for a non-activated mineral
I_x	the integral intensity of a diffraction peak for the mechanically activated mineral
P_{CO2}	CO_2 partial pressure (atm)
P_{80}	80% passing size (μm)
R_x	CO_2 sequestration reaction efficiency (%)
T	temperature (°C)
t_M	milling residence time (min)
t_C	autoclave carbonation time (hour)
W_N	specific milling energy input ($kWht^{-1}$)
$W_{O(L)}$	the total scale energy consumption of a mill, which is used in an industrial process ($kWht^{-1}$)
X_{CO_2}	the weight percent of CO_2 in the solid products (%)
θ	the scattering angle, and 2θ is the peak position in X-ray diffraction pattern
β_S	the total-size-integral breadth
β_D	the total-strain-integral breadth
ε	the micro-strain
ε_A	the percent weight added if all available Mg^{2+}, Ca^{2+} and Fe^{2+} cations are converted into carbonates (%)
λ	the wavelength
η	CO_2 avoidance ratio

(i.e. olivine, serpentine) with huge CO_2 sequestration capacity (Hitch et al., 2010). In general, an active mine includes mining, ore processing, rock transportation, and waste materials disposal. Add a MC facility after ore processing can easily use the fine-sized tailings as feedstock for CO_2. The CO_2 would be transported from its source after CO_2 capture and compress (Jacobs, 2014). The sharing of same infrastructure with the mine and the added value of metal products decrease the cost of MC (Lackner et al., 2008). At the same time, by applying MC, the mining industry can potentially lower the mine cut-off grade and render marginal projects economically feasible and environmentally attractive (Hitch and Dipple, 2012). In a case study of Turnagain Nickel Deposit located at northern BC, the theoretical carbonation potential was estimated to be 81.9 Mt CO_2 over a 29-year mine life (Hitch et al., 2010). The integrating mineral carbonation process yielded a NPV of $131.5 million at a discount rate of 8%, with an operating cost of 82.5 $ t^{-1} CO_2 (Hitch and Dipple, 2012). However, the parameters of these studies were assumed on the basis of literature data, which may not applicable to the mine waste materials with complex mineralogy. Relative accurate and decent estimations can be obtained through developing experimental tests on the specific mine wastes, and using advanced MC techniques.

Minerals hosed in ultramafic rocks are commonly disseminated and need to be liberated prior to processing. In order to liberate fine-grained complex ores, grinding below 15 μm is required (Gao et al., 2002). Instead of conventional ball mills, high intensity mills are required to optimize milling efficiency relative to energy consumption. The application of high intensity mills for regrinding in mineral processing makes mechanical activation as a pre-treatment method suitable for an integrated mineral carbonation process. Fig. 1 shows the concept of an integrated mineral carbonation process in a nickel deposit with mechanical activation as pre-treatment.

Mechanical activation means using mechanical energy (i.e. intensive grinding) to enhance a reaction (Baláž, 2008). Research on the use of mechanical activation on magnesium silicates is constantly being advanced under various milling conditions (Baláž et al., 2008; Haug, 2010). Initially, the studies of mechanical activation has been focus on pure minerals, such as olivine (Kleiv and Thornhill, 2016; Li and Hitch, 2016a), serpentine (Trapasso et al., 2012; Zulumyan et al., 2011). Most recently, the ultramafic rocks with a mixture of several magnesium silicates has rouse the attention (Li and Hitch, 2016b, 2016c, 2015; Rigopoulos et al., 2015). All these studies recognized that, mechanical activation produces a large surface area and introduces imperfections to crystal structure in the mineral. However, the economic analysis mechanical activation as pretreatment in the integrated mineral carbonation process remains to be undertaken.

The aim of this study is to determine the feasibility of an integrated mineral carbonation process with mechanical activation as a pretreatment method. A case study was developed for the Turnagain Nickel Deposit, and the analysis was based on the economic model developed by Hitch and Dipple (2012). An IsaMill was chosen for mechanical activation, because this type of mill has been successfully applied for ultrafine grinding in mineral processing. A direct aqueous carbonation process was used to test the efficiency of mechanical activation, because it provides the most successful carbonation conversion in the literature to date.

2. Materials and experiments

2.1. Material

The mine waste material (TAW) studied in this research comes from drill core 06110 at the Turmagain project, Hard Creek Nickel (HCN), Canada. X-ray powder diffraction (XRPD) analysis revealed the material to be composed of approximate 64.7% Forsterite (Mg_2SiO_4), 29.6% Lizardite ($Mg_3Si_2O_5(OH)_4$). Small amount of accessory minerals like magnetite, quartz and brucite were also found in the sample. As analyzed by X-ray fluorescence, the main oxides of the material were 46.64% MgO, 38.70% SiO_2, 10.39% Fe_2O_3, 0.671% Cr_2O_3, 0.30% CaO, 0.16% MnO, 0.15% Al_2O_3, and 0.03% TiO_2,. The loss on ignition (LOI) up to 1000 °C was 4.09%. The total carbon content tested using Leco method was 0.05%. Through a mass balance study, 81% MgO was shown to be of forsterite structure and 19% from lizardite. The top particle size of the material was 106 μm, and its specific surface area was 3.19 m^2 g^{-1}.

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