

Carbon Mineralization in Ultramafic Tailings, Central British Columbia: A Prospect for Stabilizing Mine Waste and Reducing Greenhouse Gas Emissions

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Introduction

The goal of this research is to assess the prospect of reducing the costs and risks associated with the storage of ultramafic mine tailings by sequestering carbon dioxide (CO₂) through carbon mineralization. Herein, the tailings are physically stabilized by the rapid formation of secondary magnesium-carbonate minerals, which act as cement. The magnesium ions are sourced from minerals found within ultramafic tailings, and once released into water, can react with dissolved CO₂ (specifically HCO₃⁻) to safely sequester the greenhouse gas in mineral form (e.g., MgCO₃·3H₂O). These cement-forming reactions can be accelerated by exposing the tailings to a CO₂-rich gas (Harrison et al., 2013), such as the flue gases produced by onsite power generators. In addition to the partial pressure of CO₂ within the gas that the tailings are exposed to, the reactivity of the magnesium minerals can also be rate-limiting. The pH dependent dissolution rate of brucite (Mg(OH)₂) is several orders of magnitude greater than that of other magnesium minerals that are commonly found within ultramafic tailings (e.g., serpentine and olivine; Power et al., 2013). Therefore the significance of brucite's presence, even in trace amounts, is that it offers a source of quickly dissolving magnesium ions for rapid and inexpensive tailings cementation through carbon mineralization.

In this study, the prospect of stabilizing brucite-bearing ultramafic mine tailings through carbon mineralization is assessed by testing their unconfined compressive strength as a proxy for stability after they have been compacted and exposed to a 10% CO₂ gas while partially saturated with water. The effect of the initial brucite abundance within 'pro-

spective tailings' (i.e., finely ground exploration pulps from the Baptiste nickel deposit in FPX Nickel Corp.'s Decar property, central British Columbia; Britten, 2017) on unconfined compressive strength after exposure to the 10% CO₂ gas stream is studied. The consumption of brucite is used as evidence for the sequestration of CO₂ through carbon mineralization (in future work, the increase in carbon content [wt. % C] will also be used as evidence). It should be noted that in a separate study, it has been demonstrated that brucite-rich zones of the Baptiste nickel deposit can be identified and targeted through geometallurgical analysis (described in Dipple et al., 2002) that projects mineral abundance from whole-rock geochemical data collected during the exploration phase of mining.

Methods

To examine proof of concept, cylinders (5.0 cm in height, 2.5 cm in diameter) of compacted prospective tailings, henceforth referred to simply as tailings, were prepared with brucite abundances that ranged from 0.2 to 10 wt. %. In addition to the five prospective tailings samples, there was one sample from tailings produced by a nickel-iron alloy recovery method that was based on magnetic susceptibility. The mineralogical composition of each starting material is shown in Table 1 and was determined through the Rietveld method using powder X-ray diffraction (XRD) data (Wilson et al., 2009). The cylinders were prepared by placing ~2.5 g of tailings in a hollow cylinder before compacting the material with a piston under a force of ~100 psi, then wetting the newly compacted surface with deionized water, and then repeating the process to form laminates of undersaturated compacted tailings. The pore space in the compacted tailings was saturated to a level of approximately ~50% with deionized water. The compacted tailings were placed in a chamber with continuous flow through of a hydrated 10% CO₂ and 90% N₂ gas at a flow rate of

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Table 1. The mineralogical composition of samples from the Baptiste nickel deposit, central British Columbia, which were used as raw materials for producing cemented tailings cylinders. All samples, except D-43, are exploration pulps. Sample D-34 consists of tailings produced by a nickel-iron alloy recovery method that was based on magnetic susceptibility.

Sample ID	Brucite (wt. %)	Magnetite (wt. %)	Olivine (wt. %)	Serpentine (wt. %)	Diopside (wt. %)
1423072	10.1	4.1	3.4	81.8	0.5
1423128	6.8	3.6	8.3	81.3	0
1423127	4.6	2.2	11.6	81.7	0
1423090	1.8	1.8	11	84.6	0.8
1423111	0.2	4.6	3.9	88.9	2.4
D-43	0.9	0	3.1	94.6	1.5

~10 mL/min for three weeks. The chamber volume was ~5 L and 4–8 cylinders were in it at a time. The tailings cylinders were then allowed to dry for several days in open air in the laboratory ($p\text{CO}_2 = 0.04\%$) before their porosity and unconfined compressive strength were measured. The total porosity of each sample was calculated from independent measurements of bulk (geometric) and matrix (helium-pycnometry) density (Kennedy et al., 2009), and the unconfined compressive strength tests were conducted with a loading rate of 34 kg/min (75 lb./min) in a uniaxial press. Figure 1 shows a tailings cylinder after failure. Ongoing work includes measuring the carbon content of selected tailings cylinders as a function of distance from the surface by collecting aliquots at intervals along the radius.

Results and Discussion

From Figure 2 it can be seen that the initial amount of brucite within the tailings had a remarkable influence on the compressive strength of the tailings cylinders after exposure to a 10% CO_2 environment. This is inferred to be due to the transformation of brucite into secondary magnesium-carbonate cement phases. The transformation of brucite, rather than other minerals such as serpentine, is supported by XRD results that show the abundance of brucite significantly decreases after exposure to a 10% CO_2 environment (Figure 3). Samples with relatively low initial brucite content (~0.5 wt. %) yielded unconfined compressive strengths of ~50–100 psi, whereas samples with initial brucite contents of ~5 wt. % had unconfined compressive strengths of ~1000 psi. Interestingly, the sample with highest initial brucite content (10 wt. %) did not yield the highest strength. This is hypothesized to be because CO_2 was consumed by reaction before it was able to fully penetrate to the core of the cylinder; this hypothesis will be tested in the future by assessing the carbon content of the cylinders along their radii. A relationship between total porosity and compressive strength may exist (Figure 2), however, the physical mechanisms of strength development require further investigation.



Figure 1. A tailings cylinder after being compressed until failure. The sample was cemented by the formation of secondary magnesium-carbonate minerals after exposure to a 10% CO_2 gas stream for three weeks.

Conclusions and Future Work

These lab-scale tests have demonstrated that exposing partially saturated and compacted ultramafic tailings to a 10% CO_2 gas stream can effectively stabilize the waste and sequester CO_2 when trace amounts of brucite are initially present. An unconfined compressive strength of up to 1000 psi was achieved with an initial brucite content of ~5 wt. %, and even samples with an initial brucite content of ~0.5 wt. % exhibited unconfined compressive strengths of ~50–100 psi. If this process is utilized at a mine site, the tailings become resistant to liquefaction under stress due to the formation of the magnesium-carbonate cement and development of compressive strength, potentially reducing the risk of a tailings dam failure. Furthermore, these results encourage collaboration between science and engineering to assess alternative and less costly tailings storage facility designs that exploit the ability of brucite-bearing tailings to become self-stabilizing after adequate reaction with CO_2 .

Due to the scale of tailings production at mine sites, the reaction between CO_2 and even trace amounts of brucite in the tailings can generate significant greenhouse gas emission offsets. Assuming a large nickel mine produces 10 Mt of tailings per year and has an average brucite content of 2 wt. %, up to 150 000 tonnes of CO_2 can be sequestered per year. To evaluate the prospect of achieving carbon-neutral nickel mining in BC by the reaction of brucite in tailings

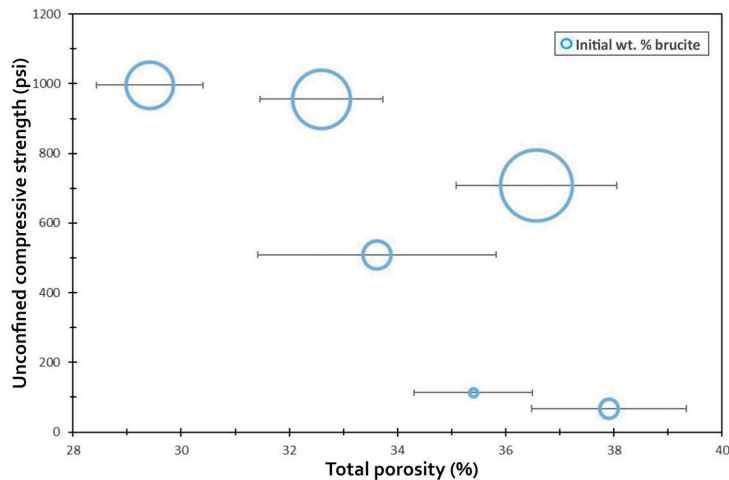


Figure 2. The compressive strength of tailings cylinders after exposure to a 10% CO₂ environment for three weeks. The size of the circle represents the initial brucite content, and the total porosity is the sum of the connected and isolated porosities.

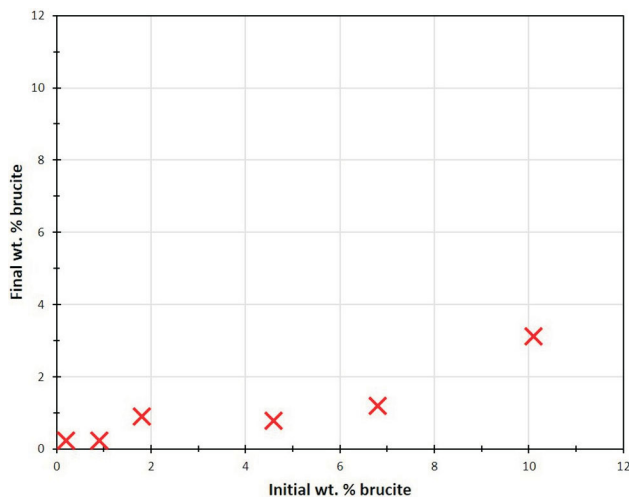


Figure 3. The initial wt. % brucite content of the tailings versus their final wt. % brucite content after being exposed to a 10% CO₂ environment for three weeks. Determined by Rietveld method using X-ray diffraction analysis data.

with CO₂, the CO₂ emission and tailings production data from the Mount Keith nickel mine in Australia can be considered. At this mine, 11 Mt of tailings are produced per year, and 140 000 tonnes of CO₂ are produced per year by mining trucks (accounting for 40% of total mine emissions, with the remainder accounted for by onsite electricity generation from natural gas for ore processing facilities; Wilson et al., 2014). Furthermore, Wilson et al. found that approximately 40 000 tonnes of CO₂ are sequestered per year at Mount Keith due to the ‘accidental’ reactions between atmospheric CO₂ and brucite found in the mine tailings. The authors also found that brucite was not being fully consumed by reaction with atmospheric CO₂ before being buried by subsequent layers of tailings. If the tailings were allowed to react for a longer period of time, or if they were deposited in thinner layers, then up to 120 000 tonnes of

CO₂ could be sequestered just by reaction of brucite with atmospheric CO₂. Therefore, carbon-neutral nickel mining in BC could potentially be achieved if hydroelectricity is used at ore processing facilities and mining truck emissions are offset by fully reacting tailings containing an average of 2 wt. % brucite with CO₂.

Future work will narrow in on the threshold parameters for stabilization and investigate other methods of manufacturing cemented tailings cylinders. Processes of tailings compaction and CO₂ delivery will be assessed to find a procedure that more closely resembles that which could be readily adopted at mine sites. The diffusion rates of CO₂ into the tailings as a function of both brucite content and permeability will be modelled. Imaging and chemical characterization of the magnesium-carbonate cement phases will be conducted through X-ray mapping and electron microprobe analysis to better understand the mechanisms of stabilization. Furthermore, the thermodynamic stability of the cement phases in various environments will be studied through geochemical modelling.

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