The Mineralogy and Chemical Properties of Sedimentary Waste Rocks with Carbon Sequestration Potential at the Selinsing Gold Mine, Pahang

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ABSTRACT

Waste rocks are a non-economical by-product of mining operations, which can lock up carbon dioxide into a carbonate form and thereby help reduce greenhouse gases emissions. The aims of this research are to determine the mineral and chemical composition of the sedimentary waste rocks of gold mines and to classify the potential of silicate minerals to be a feedstock for carbonation mineralization. The sampling was undertaken at the Selinsing gold mine, where waste rocks were collected from the waste dump, stockpiles, the borrow pit, and the main pit. The mineralogical and chemical component of the sedimentary waste rocks were explored using X-ray diffraction and energy dispersive X-ray spectroscopy. The findings indicated that the presence of divalent cations, of 55.12% for CaO, 9.09% for MgO, and 16.24% for Fe_2O_3 from gold mine waste, capable of sequestering carbon dioxide into calcium, magnesium and iron carbonates, respectively, through carbonation of mineral. The domination of silicate minerals such as quartz, muscovite, kaolinite, chlorite, albite, and carbonate minerals such as calcite, have been found to be widespread in sedimentary waste rocks. However, the natural silicates (chlorite, muscovite) and carbonates (calcite) are potential minerals which can be consumed as feedstock for carbonation processes because they contain the magnesium, iron, and calcium elements which can form stable carbonates in the

presence of carbon dioxide. The mineralogy and chemical composition of sedimentary waste rocks from the Selinsing gold mine provides a better understanding of the future carbonation reaction to sequester more carbon dioxide in response to climate change.

Keywords: Carbonation reaction, carbon sequestration, chemical composition, mineralogy, sedimentary rock, Selinsing gold mine

INTRODUCTION

Carbon dioxide (CO_2) emissions are at a current level of 257.69 million tonnes (Mt), as of 2014, and are expect to increase to 12.1 tonnes of CO_2 emission per capita by 2020 (Zaid et al., 2015). To reduce the release of CO_2 into the environment, carbon capture and storage (CCS) is one reliable technique which can help achieve 20% CO_2 emission reductions (Benson & Cole, 2008), made possible by storing CO_2 permanently in a stable carbonate form (Arce et al., 2017; Lackner et al., 1995; Renforth, 2011). The formation of carbonate requires potential divalent cations, such as magnesium, iron, and calcium (Mg-Fe-Ca), which are more reactive with CO_2, in term of forming carbonate minerals (Lechat et al., 2016; Wilson et al., 2009). The availability of divalent cations in mine waste rocks from ultramafic-hosted ore residue, are usually favorable for mineral carbonation (Hitch et al., 2010). Therefore, the waste of the mine can be used as potential feedstock for carbon sequestration.

Rocks and minerals play an important part, as reactive agents, in decreasing CO_2 discharge during carbon sequestration (Li & Hitch, 2015; Renforth et al., 2011; Wilson et al., 2009). For instance, igneous rocks such as basalts contain silicate minerals, including feldspars, plagioclase, pyroxenes, and others, which can react with dissolved CO_2 to form carbonates (Jorat et al., 2017). Additionally, sedimentary rock such as shales have the potential to store significant quantities of CO_2 dissolved in liquid formation, trapped by mineral carbonation or absorbed into organic mixtures or the surfaces of minerals (Busch et al., 2008).

In this study, the potential of obtaining sedimentary rock from gold mining waste has been explored as a potential feedstock for carbon sequestration through the mineral carbonation process. This study's objective are to determine the mineral and chemical compositions of waste rock samples from various types of gold mine waste, and to classify the potential of silicate minerals as a feedstock for carbonation mineralization in the waste rock samples of gold mine waste.

MATERIALS AND METHODS

The Sampling Area of the Selinsing Gold Mine

Field sampling was undertaken at an active gold mining area in Selinsing, Pahang with coordinate of N 4°15'0'', E 101°47'10'', which itself is in a prominent gold mining region

in Peninsular Malaysia (Makoundi et al., 2014; Yeap, 1993). Waste rock samples had been collected at seven sampling points which consisted of stockpiles of high grade (HG), lower grade (LG), super lower grade (SLG), waste dump, borrow pit, and the main pit which consisted of open pit 1 and open pit 2 (Figure 1). The host rock at the Selinsing gold mine consists of sedimentary rocks, including siltstone, argillite, phyllite, carbonaceous shale, grey-black limestone, sandstone, and tuffaceous conglomerate (Makoundi et al., 2014; Pour & Hashim, 2015). Minerals such as quartz (SiO_2), dolomite [$CaMg(CO_3)_2$], and pyrite (FeS_2) are all widely distributed in gold mines (Makoundi et al., 2014).
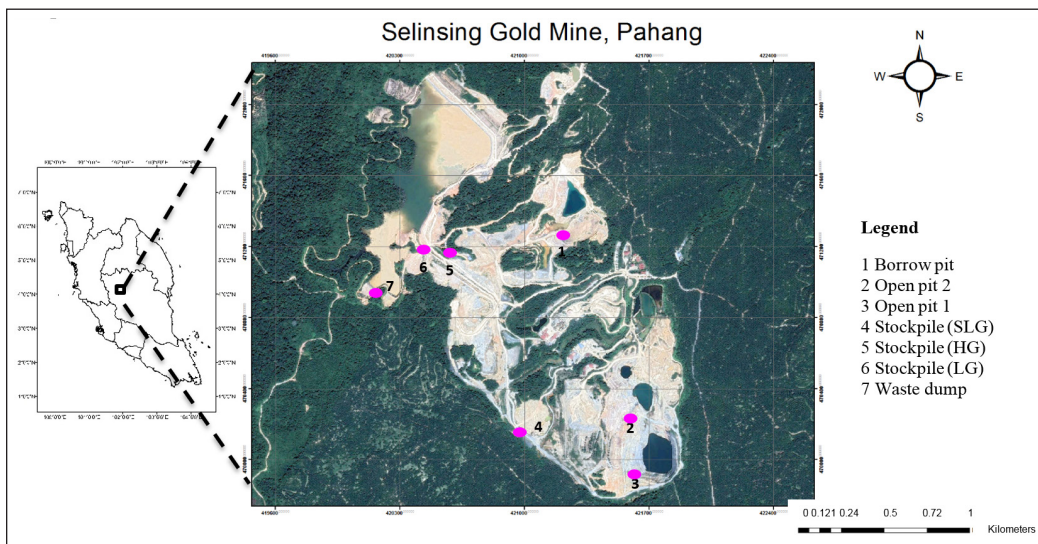

Figure 1. Study area consist of seven sampling points at gold mine of Selinsing, Pahang, Malaysia using geographic information system (GIS)

Mineralogical Analysis

Prior to analysis, waste rocks were first crushed manually, grounded into fine particles, and then sieved to a one mm size component using grain sieves. Then the sieved samples were grounded again into a very fine powder form, using an octagonal agate mortar and pestle made of natural quartz. About 1 ± 0.5 g of the fine powder samples were placed in a 2.5 cm diameter circular specimen holder of polymethylmethacrylate (PMMA), before being attached to an X-ray machine. The fine powder of waste rocks was analysed using an X-ray diffractometer (XRD) instrument (model Philips X'Pert Pro Pranalytical-PW3440/60, Netherlands) at a 1°/min rate (0.02° step size), counting for 0.2 s per step over the scattering angle range between 5-50°. The detection limit range was between 1 to 2%. The integrated peak areas intensity from the single peak function was determined using Diffrac AT EVA software version 9.0, and the d-spacing was identified using the OriginPro 8 software (Originlab Corporation, Northampton, UK).

Chemical Analysis

A chemical composition analysis was conducted using an energy dispersive X-ray (EDX) to measure in a percentage the elemental composition of waste rock. The whole waste rocks from the Selinsing gold mine were analysed in a fine powder form (< 2 mm size fraction). Samples were made to be as homogenous as possible, so to minimize error while performing EDX. About 1 g of homogenous fine powder samples were introduced to the EDX machine, for the purpose of phase determination. The values obtained for Ca, Mg, Fe, Si, Al, and K were then converted in terms of oxides correspondence, with 0.1% detection limits.

RESULTS AND DISCUSSION

Mineralogy and Chemical Composition of Waste Rock

Seven types of crystalline phases were classified in the waste rock samples drawn from the various kinds of gold mining wastes at Selinsing, Pahang (Figure 2). The mineralogy of the gold mining waste consists of silicate minerals, such as quartz (SiO_2), muscovite [$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$], chlorite [$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$], kaolinite [$Al_2Si_2O_5(OH)_4$], albite ($NaAlSi_3O_8$); and carbonate minerals such as calcite ($CaCO_3$). The highest peak of quartz, signified a major mineral found to be widespread in the waste rock of gold mining wastes. This is because quartz is known to be a primary mineral that is resistant to weathering and commonly discovered in every type of rock (Kusin et al., 2018; Shamshuddin, 2011).
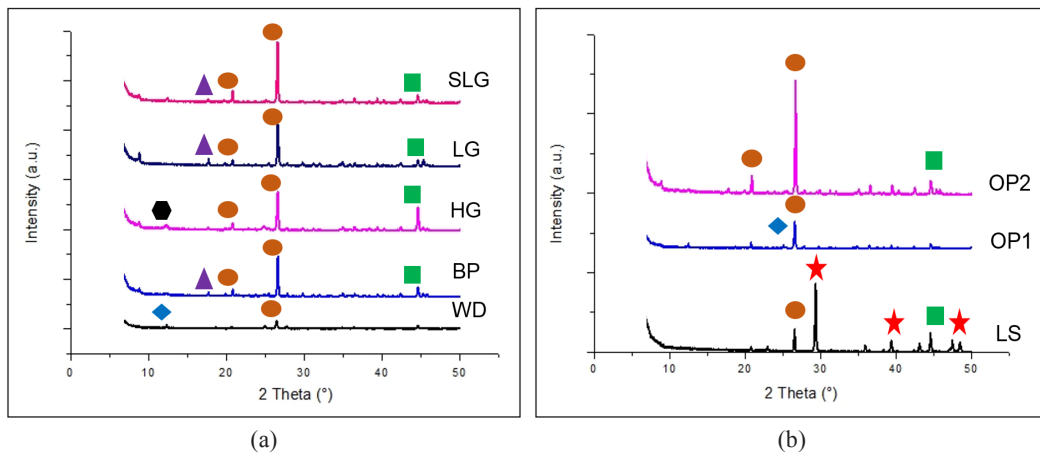

(a)   (b)

Figure 2. The XRD diffractograms of the waste rock from: (a) the waste dump (WD), the borrow pit (BP), stockpile (HG, LG, SLG); and from (b) the main pit, included limestone (LS), open pit 1 (OP1), and open pit 2 (OP2). The inserted symbols indicate the peaks for all type of mining wastes, with the orange circle being quartz, the green square being graphite, the purple triangle being muscovite, the red star being calcite, the blue diamond being chlorite, and the black hexagon being kaolinite

Results have shown a domination of silicate minerals, explained by high percentage of SiO_2 and Al_2O_3, which were widely discovered at the stockpile SLG and at the waste dump at 71.06% and 24.35% respectively (Table 1). A high percentage of SiO_2 and Al_2O_3 shows the existence of muscovite, kaolinite, chlorite, and albite in gold mining wastes. This is because some of these minerals are formed during the chemical weathering of alumino-silicates (Kusin et al., 2017; Shamshuddin, 2011), which are found in different types of rock including conglomerate, phyllite, carbonate, shale, and tuffs (Makoundi et al., 2014; Pour & Hashim, 2015). Since the host rock at the Selinsing gold mine comes from sedimentary rocks, those minerals are expected to be found in each type of mining waste.

Table 1
The chemical composition of waste rock, extracted from gold mining waste at the Selinsing, Pahang

| Compound (%)	Sampling Location							
	Waste Dump	Borrow Pit	Stockpile HG	Stockpile LG	Stockpile SLG	Limestone	Open Pit 1	Open Pit 2
MgO*	5.74*	-	-	-	-	1.14*	2.21*	-
SiO_2	54.81	62.91	70.17	61.35	71.06	22.92	61.53	68.34
CaO*	-	-	-	-	-	55.12*	-	-
Fe_2O_3*	5.71*	4.85*	-	-	-	-	3.89*	1.79*
Al_2O_3	24.35	22.27	24.17	21.62	14.55	2.60	18.64	18.23
K_2O	3.94	6.51	5.10	8.91	4.85	-	5.09	6.82
SO_3	-	-	0.57	3.31	-	0.26	-	1.11

Note: *indicate the divalent cation which can influence the mineral carbonation process

The Potential of Silicate Minerals for Mineral Carbonation

This studies' findings have indicated that the total 9.09% of MgO can be explained through the presence of chlorite in the waste rocks of the waste dump, limestone, and open pit 1, while the 55.12% of CaO apparently come from calcite in limestone (Table 1). Both MgO and CaO are potential divalent cations required for the mineral carbonation process to occur (Lechat et al., 2016; Wilson et al., 2009). The carbonation reaction of MgO and CaO in the existence of CO_2, producing carbonate minerals such as magnesium carbonate ($MgCO_3$) (reaction 1) and calcium carbonate ($CaCO_3$) (reaction 2), respectively (Lackner et al., 1995; Lechat et al., 2016; Power et al., 2013; Renforth, 2011; Wilson et al., 2009):

$$MgO + CO_2 \rightarrow MgCO_3 \qquad \text{(Delta Hr = 118 Kj/mol)} \qquad (1)$$

$$CaO + CO_2 \rightarrow CaCO_3 \qquad \text{(Delta Hr = 179 Kj/mol)} \qquad (2)$$

In the context of carbon sequestration, CO_2 reacts with the divalent cation (Ca-Mg-Fe) to produce permanent carbonates (Lechat et al., 2016; Wilson et al., 2009). The results suggest that chlorite is the most promising mineral for the carbonation process, due to the presence of the divalent cation of Mg in chlorite, which makes it capable of reacting with CO_2 to form a carbonate mineral, as proven in the reaction below (Hitch et al., 2010; Power et al., 2013; Renforth et al., 2011):

$$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8 + 6CO_2 \rightarrow 6(Mg,Fe,Al)CO_3 + 4(Si,Al)O_2 + 4H_2O$$
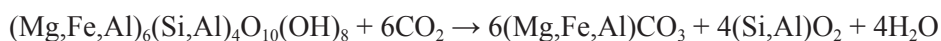
The finding is in line with recent research, which has indicated that chlorite is the potential silicate mineral containing the divalent Mg, which is promising for the carbonation of mineral (Hasan et al., 2018). Furthermore, carbon sequestration is very effective in the Mg and Ca-rich minerals included in mining waste, in term of sequestering more CO_2 (Assima et al., 2014; Wilson et al., 2009). The occurrence of silicate minerals of Mg in the waste dump, and in open pit 1, indicates that CO_2 can be sequestered to form a magnesium carbonate such as magnesite ($MgCO_3$) (Jacobs, 2014). Therefore, the availability of chlorite in gold mining waste, is a potential silicate minerals which can be consumed as feedstock for the mineral carbonation process.

Carbonate minerals such as calcite are present in the limestone extracted through gold mining, because it is favorable in all types of rock, including in the sedimentary rocks of the Selinsing gold mine (Makoundi et al., 2014). In carbon sequestration, calcite may act as a reservoir for carbon storage, because it is already in a stable form. Accordingly, CO_2 is naturally stored in limestone rock (Mani et al., 2008).

The highest percentage of ferric oxide (Fe_2O_3) has been found in the waste dump (5.71%) (Table 1), known as a potential divalent cation which can be sequestered into iron carbonate ($FeCO_3$) (Vogeli et al., 2011). The total 16.24% of Fe_2O_3, is explained through the presence of muscovite at all sampling points, and of chlorite at the main pit and the waste dump (Figure 2). Therefore, the Fe-silicate minerals in gold mining wastes, such as muscovite and chlorite, can be utilized as feedstocks for enhancing the process of mineral carbonation.

CONCLUSION

This study describes the mineralogy and chemical composition of sedimentary waste rocks from gold mining waste, in term of their potential for carbon sequestration. The waste of the Selinsing gold mine in Pahang has the potential for permanent CO_2 storage, due to the presence of divalent cations, including MgO at 9.09%, CaO at 55.12%, and Fe_2O_3 at 16.24%, which can promote the formation of magnesium, calcium, and iron carbonate, respectively, through the carbonation process. The presence of natural silicate minerals like chlorite and muscovite, and of carbonate minerals like calcite in gold mine waste, can be

potential feedstock for carbon sequestration. This is because the minerals are rich in the Mg, Fe, and Ca divalent cations, which are effective in the mineral carbonation process. Therefore, the potential of mineral and chemical components of gold mining waste for supporting the mineral carbonation process, can help sequester long term CO_2 storage.

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REFERENCES

Arce, G. L. A. F., Neto, T. G. S., Ávila, I., Luna, C. M. R., José, C. S., & João, A. C. J. (2017). Influence of physicochemical properties of Brazilian serpentinites on the leaching process for indirect CO_2 mineral carbonation. *Hydrometallurgy*, *169*(May), 142-151.

Assima, G. P., Larachi, F., Molson, J., & Beaudoin, G. (2014). Emulation of ambient carbon dioxide diffusion and carbonation within nickel mining residues. *Minerals Engineering*, *59*(May), 39-44.

Benson, S. M., & Cole, D. R. (2008). CO_2 sequestration in deep sedimentary formations. *Elements*, *4*(5), 325-331.

Busch, A., Alles, S., Gensterblum, Y., Prinz, D., Dewhurst, D. N., Raven, M. D., & Krooss, B. M. (2008). Carbon dioxide storage potential of shales. *International Journal of Greenhouse Gas Control, 2*, 297-308.

Hasan, S. N. M. S., Kusin, F. M., Shamsuddin, J., & Yusuff, F. M. (2018). Potential of soil, sludge and sediment for mineral carbonation process in Selinsing gold mine, Malaysia. *Minerals, 8*(2018), 257-270.

Hitch, M., Ballantyne, S. M., & Hindle, S. R. (2010). Revaluing mine waste rock for carbon capture and storage. *International Journal of Mining, Reclamation and Environment*, *24*(1), 64-79.

Jacobs, A. D. (2014). *Quantifying the mineral carbonation potential of mine waste material: A new parameter for geospatial estimation* (Doctoral thesis). University of British Columbia, Vancouver, Canada.

Jorat, M. E., Kolosz, B. W., Goddard, M. A., Sohi, S. P., Akgun, N., Dissanayake, D., & Manning, D. A. C. (2017). Geotechnical requirements for capturing CO_2 through highways land. *International Journal of GEOMATE*, *13*(35), 22-27.

Kusin, F. M., Rahman, M. S. A., Madzin, Z., Shamsuddin, J., Mohamat-Yusuff, F., Ariffin, M., & Zahar, M. S. M. (2017). The occurrence and potential ecological risk assessment of bauxite mine-impacted water and sediments in Kuantan, Pahang, Malaysia. *Environmental Science and Pollution Research*, *24*(2), 1306-1321.

Kusin, F. M., Azani, N. N. M., Hasan, S. N. M. S., & Sulong, N. A. (2018). Distribution of heavy metals and metalloid in surface sediments of heavily-mined area for bauxite ore in Pengerang, Malaysia and associated risk assessment. *Catena*, *165*(2018), 454-464.

Lackner, K. S., Wendt, C. H., Butt, D. P., Joyce, E. L., & Sharps, D. H. (1995). Carbon dioxide disposal in carbonate minerals. *Energy*, *20*(11), 1153-1170.

Lechat, K., Jean-Michel, L., Molson, J., Beaudoin, G., & Hébert, R. (2016). Field evidence of CO_2 sequestration by mineral carbonation in ultramafic milling wastes, Thetford Mines, Canada. *International Journal of Greenhouse Gas Control*, *47*(2016), 110-121.

Li, J., & Hitch, M. (2015). Ultra-fine grinding and mechanical activation of mine waste rock using a high-speed stirred mill for mineral carbonation. *International Journal of Minerals, Metallurgy and Materials*, *22*(10), 1005-1017.

Makoundi, C., Zaw, K., Large, R. R., Meffre, S., Chun-Kit, L., & Hoe, T. G. (2014). Geology, geochemistry and metallogenesis of the Selinsing gold deposit, central Malaysia. *Gondwana Research*, *26*(1), 241-261.

Mani, D., Charan, S. N., & Kumar, B. (2008). Assessment of carbon dioxide sequestration potential of ultramafic rocks in the greenstone belts of southern India. *Current Science*, *94*(1), 5-60.

Pour, A. B., & Hashim, M. (2015). Structural mapping using PALSAR data in the Central Gold Belt, Peninsular Malaysia. *Ore Geology Review*s, *64*(2015), 13-22.

Power, I. M., Harrison, A. L., & Dipple, G. M. (2013). Carbon mineralization: From natural analogues to engineered systems. *Reviews in Mineralogy and Geochemistry*, *77*(1), 305-360.

Renforth, P. (2011). *Mineral carbonation in soils engineering the soil carbon sink* (Doctoral thesis). Newcastle University, United Kingdom.

Renforth, P., Washbourne, C. L., Taylder, J., & Manning, D. A. C. (2011). Silicate production and availability for mineral carbonation. *Environmental Science and Technology*, *45*(2011), 2035-2041.

Shamsuddin, J. (2011). *Methods in soil mineralogy*. Serdang, Malaysia: UPM Press.

Vogeli, J., Reid, D. L., Becker, M., Broadhurst, J., & Franzidis, J. P. (2011). Investigation of the potential for mineral carbonation of PGM tailings in South Africa. *Minerals Engineering*, *24*(12), 1348-1356.

Wilson, S. A., Dipple, G. M., Power, I. M., Thom, J. M., Anderson, R. G., Raudsepp, M., & Southam, G. (2009). Carbon dioxide fixation within mine wastes of ultramafic-hosted ore deposits: Examples from the Clinton Creek and Cassiar chrysotile deposits, Canada. *Economic Geology*, *104*(1), 95-112.

Yeap, E. B. (1993). Tin and gold mineralizations in Peninsular Malaysia and their relationships to the tectonic development. *Journal of Southeast Asian Earth*, *8*(1-4), 329-348.

Zaid, S. M., Myeda, N. E., Mahyuddin, N., & Sulaiman, R. (2015). Malaysia's rising GHG emissions and carbon 'lock-in' risk: A review of Malaysian building sector legislation and policy. *Journal of Surveying, Construction and Property*, *6*(1), 1-13.