Introduction

As concerns over climate change grow, Carbon Geological Sequestration (CGS) is becoming more widely acknowledged as a crucial tactic for lowering atmospheric carbon dioxide (CO_2) levels (Bashir, Ali et al. 2024). Among the available methods, carbon mineralization stands out due to its ability to transform CO_2 into stable solid carbonates during the interaction between CO_2 and silicate minerals (Yuen, Sharratt et al. 2016, Raza, Glatz et al. 2022). This process has also been known as natural chemical weathering and/or alteration of particular rocks occurring at surfaces, near-surface, or underground, in geologic periods.

Carbon mineralization is primarily driven by CO_2-reactive magnesium and calcium-rich silicate minerals, which are usually found in mafic-ultramafic igneous rocks, especially basalts (Hills, Tripathi et al. 2020, Sandra Ó, Bergur et al. 2020, Gadikota 2021). The rocks contain significant amounts of olivine, plagioclase, and pyroxene. Long-term CO_2 sequestration in solid form is ensured by the breakdown of those reactive silicates during carbon dioxide exposure, resulting in the precipitation of carbonate minerals, i.e. calcite and magnesite. The resource abundance and high reactivity with carbon dioxide of basalts make them an ideal geologic candidate (Otabir, Khanal et al. 2025). Even though the CO_2 mineralization of rocks happens naturally, the process is inherently slow. Recently, there have been several enhanced techniques to accelerate CO_2 mineralization reactions and improve the carbon sequestration potential of the rocks by using physical and chemical treatments. The techniques, for example, include rock size reduction (Taksavasu, Arin et al. 2024), heat and pressure treatments (Cao, Li et al. 2024), and chemical treatments (Teir, Fogelholm et al. 2007, Kodama, Nishimoto et al. 2008).

This study focuses on the Mae Tha basaltic formation observed near the Mae Moh coal mine in northern Thailand. It was formed in the Late Cenozoic era as an emergence of volcanic activities (Sasada et al. 1987). Since rock has previously been classified as mafic igneous composition, it is believed to hold a great potential for ex-situ carbon mineralization. The study aims to investigate the CO_2 mineralization potential of this natural basalt using a chemical pH-swing pretreatment technique. The CO_2 reaction experiment is in ambient condition. In addition, this study briefly observes the mineral assemblage of the basalt under microscopic views and finds that it contains moderate-to-high proportions of olivine, plagioclase, and pyroxene as shown in Figure 1.

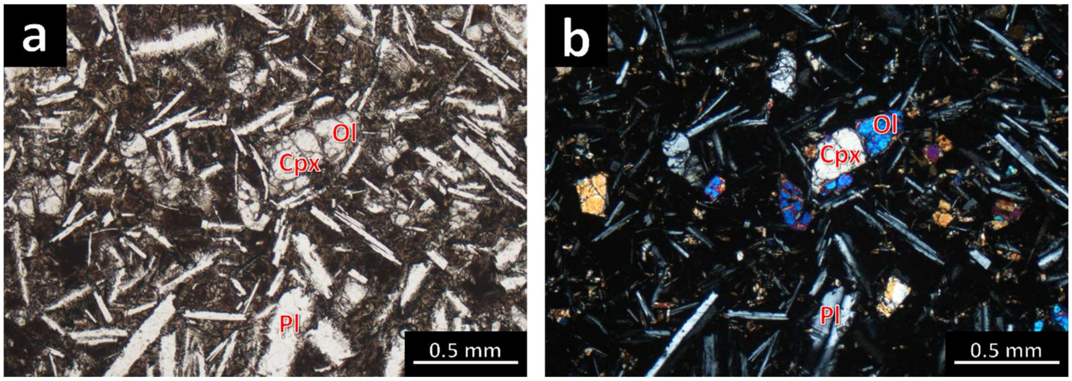

Figure 1. *Photomicrographs of Mae Tha basalt exhibiting various crystals of sub-equant olivine (Ol), tabular clinopyroxene (Cpx), and prismatic plagioclase (Pl) taken under plane-polarized light (a) and cross-polarized light (b).*

Methods

To prepare the sample test, the basalt specimens were crushed and sieved into a small particle size of under 60 mesh *(less than 0.25 mm)*. The weight of basalt powder used for the experiment is 50 grams. The experimental procedure is provided in the following and shown in Figure 2.

Dissolution stage: 50 g of basalt powder was mixed with 100 mL of 2M HCl and stirred for two hours. This process aims to leach divalent cation ions (Mg^{2+}, Ca^{+2}, Fe^{2+}) from the minerals. After that, the undissolved solid phases were filtrated out of the solution.

Purification stage: The filtrated solution was mixed with 1M NaOH to adjust the solution pH up to 5 and 9 for eliminating $Fe(OH)_3$ and $Fe(OH)_2$, respectively. This process is crucial to prevent further reactions and hinder carbonate precipitation (Reynes, Mercier et al. 2023). The pH of the solution was continually adjusted until it reached 11. The iron precipitated were carefully filtrated out of the final solution.

Carbonation stage: Carbon dioxide gaseous phase was added into the final solution under ambient conditions for an hour. The existence of new solid phases in the solution was observed. After that, the final resulting product was dried in a laboratory oven and then weighed.

Mineralogical analysis: The final solid material was determined using the X-ray fluorescence technique to check the elemental component and predict the possible mineral phase.

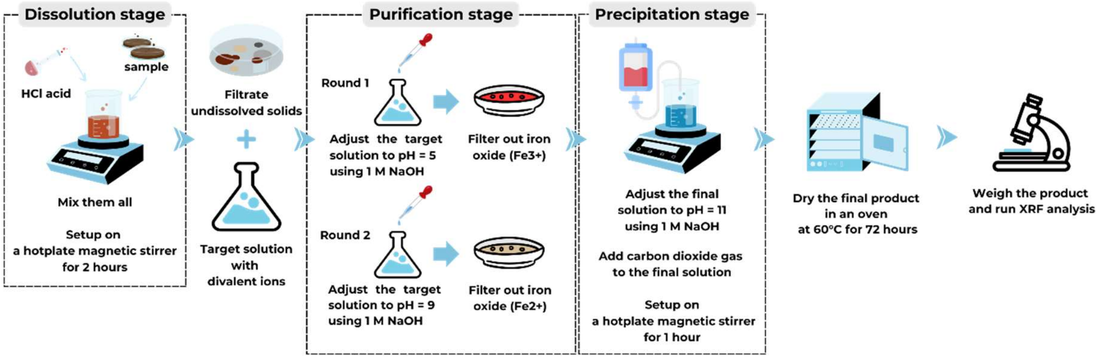

Figure 2. *Schematic of the experimental procedure consisting of three key stages: (1) Dissolution of basaltic powder in HCl, (2) Purification and eliminating Fe, and (3) Mineral carbonation under ambient conditions.*

Results and Conclusion

Mg^{2+}, Ca^{2+}, and Fe^{2+} ions were efficiently extracted during the dissolution stage with HCl, confirming the release of divalent cations from Mae Tha Basalt. The process continued through the purification stage, where iron impurities were successfully removed, as verified by XRF analysis (Table 1), showing a high concentration of Fe in the solid residue and only trace amounts, if any, remaining in the final product. In the final stage, CO_2 bubbling led to the precipitation of stable carbonate minerals, primarily magnesite, with magnesium content increasing to 12.50%. The final precipitate, assumed to be predominantly carbonates, weighed approximately 2 grams. Figure 3 illustrates the progression of solid residues through each stage of the process.

Table 1. *XRF results of initial rock sample and filtered solid materials from each experimental stage.*

Element	Initial Rock	Products of Each Stage			
		After Dissolution	1st Purification	2nd Purification	Carbonation
Si	16.41%	14.65%	1.15%	4013.33 ppm	1.20%
Al	6.84%	5.38%	4.74%	2.09%	2.57%
Fe	5.94%	4.92%	3.84%	3.44%	34.33 ppm
Ca	5.09%	3.33%	2.11%	19.71%	3.73%
Ti	1.28%	1.15%	950 ppm	220 ppm	1443.33 ppm
K	1.20%	6906.67 ppm	2740 ppm	1387.33 ppm	1.97%
Mg	8566.67 ppm	1.31%	6.29%	7.40%	12.50%
P	1813.33 ppm	1083.33 ppm	6456.67 ppm	350 ppm	890 ppm
Mn	1436 ppm	707 ppm	1368 ppm	8380 ppm	77 ppm
Cr	227.67 ppm	133 ppm	756.33 ppm	60 pp	ND
Ni	174.67 ppm	119.33 ppm	489.33 ppm	367 ppm	ND
Zn	89 ppm	78.67 ppm	77.67 ppm	41.67 ppm	7 ppm
Cu	36 ppm	26.67 ppm	58 ppm	15.33 ppm	ND

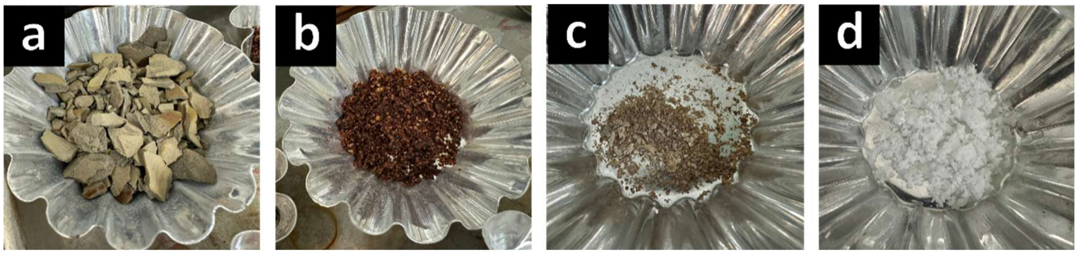

Figure 3. *Solid residuals during the experiment include: (a) Undissolved rock solid after acidic dissolution, primarily inert silicates. (b) Reddish* $Fe(OH)_3$ *precipitates at pH 5, indicating* Fe^{3+} *removal. (c) Milky-white* $Fe(OH)_2$ *precipitates at pH 9, indicating* Fe^{2+} *removal. (d) White Mg-rich carbonate precipitates after the* CO_2 *bubbling at pH 11. The final product was 2 grams in weight.*

The experimental results reveal that the pH-swing technique significantly enhances carbon mineralization in Mae Tha Basalt, promoting effective CO_2 sequestration. While further studies are needed to refine reaction conditions for industrial applications, these findings highlight the potential of Mae Tha Basalt as a promising option for large-scale carbon sequestration.

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