Introduction

Earth's ecosystems have been greatly affected since the Industrial Revolution, with a significant increase in the atmospheric concentrations of CO_2 and other greenhouse gases (GHGs) from burning fossil fuels and large amounts of emissions produced by the Cement and Steel industries (Chien et al., 2023; Joarder et al., 2023). Carbon Capture and Storage (CCS) technology is an effective strategy for mitigating climate change and has emerged as a promising strategy to address global warming (Massarweh et al., 2024). Carbon storage in the underground geological formations such as depleted hydrocarbon reservoirs, deep saline aquifers, coal beds (which can't be mined), and un-conventional shale formations offer diverse solutions and long-term stability (Bachu, 2003; Vishal et al., 2013). Carbon mineralization in igneous rocks such as Basalts and Peridotites is another potential CO_2 storage technique that does not suffer from the limitations of sedimentary formations due to their high content of divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}, Al^{2+}), favorable mineral compositions (pyroxene and olivine) and high reactivity (Kelemen et al., 2019; Snaebjornsdottir et al., 2020). Carbon mineralization methods are generally divided into two categories: i.) ex-situ, ii.) in-situ methods. In-situ mineralization involves the idea of capturing CO_2 and injecting it into reactive rocks such as mafic (basalts) and ultramafic (peridotites) where, secondary trapping mechanisms, including solubility trapping by the dissolution of CO_2 in reservoir fluid, capillary trapping by capillary forces, and mineralization by fluid-rock interactions cause CO_2 trapping depending on geological and operational conditions (Raza et al., 2016; Iglauer, 2011; Oelkers et al., 2008). The main advantage of this method is the low risk of leakage due to the rapid transformation of CO_2 into stable carbonate minerals (mineral trapping) (Goldberg et al., 2008). Currently, there are two known pilot projects for CO_2 injection into basalts in Iceland (CarbFix Project) and in the USA (Wallula Project) which demonstrate new insights for CO_2 geo-sequestration through mineralization and development of pilot projects in the Basalts for future studies (McGrail et al., 2017). The present study targets the onshore mafic basaltic rock sites that hold the potential for CO_2 storage around Western and Eastern Malaysia.

Method

The methodology of the study includes various techniques to examine the potential of CO_2 sequestration in the onshore mafic basaltic rocks found near Kuantan, Peninsular Malaysia and Sematan, Kuching, Eastern Malaysia which is demonstrated through field-scale observations, geological mapping of the suitable area, measuring the thickness and collection of rock samples from the outcrop.

1.Laboratory experiments

- The rock characterization based on geochemical properties is conducted to examine the various mineral and oxide compositions of the basalts, their characteristics & morphology, grain boundaries, fracture surfaces and surface area through (XRD, XRF, FESEM, SAP, and ICP-OES) analysis.
- The experiments based on geo-mechanical properties such as Uniaxial, Triaxial Compression Test (UCS), Brazilian Tensile Strength (BTS), Pulse-wave velocity with acoustic sensors are conducted to identify the strength/integrity, stress/strain behaviour of the rock material.

2. Petrophysical Experiments

- The experiments based on petrophysical properties such as (Porosity and Permeability) are conducted using MIP analysis for enhancing the potential for CO_2 mineralization in the subsurface formations.

3. Fluid-rock Experiments

- The Core-flooding experiments using the relative Permeability system are carried out to demonstrate the fluid-rock interactions, relative permeability, porosity at reservoir conditions, wettability, fluid flow with the (core samples and core plugs) at various temperature and pressure limits.
- The experiments using batch reactors with the (powdered samples) and brines are carried out at various pressures, temperatures, and pH conditions to understand the properties of CO_2, mineralization, and reaction kinetics processes through which it undergoes dissolution of the divalent cations as bicarbonates which precipitate to form solid carbonates such as calcite, magnesite, dolomite.

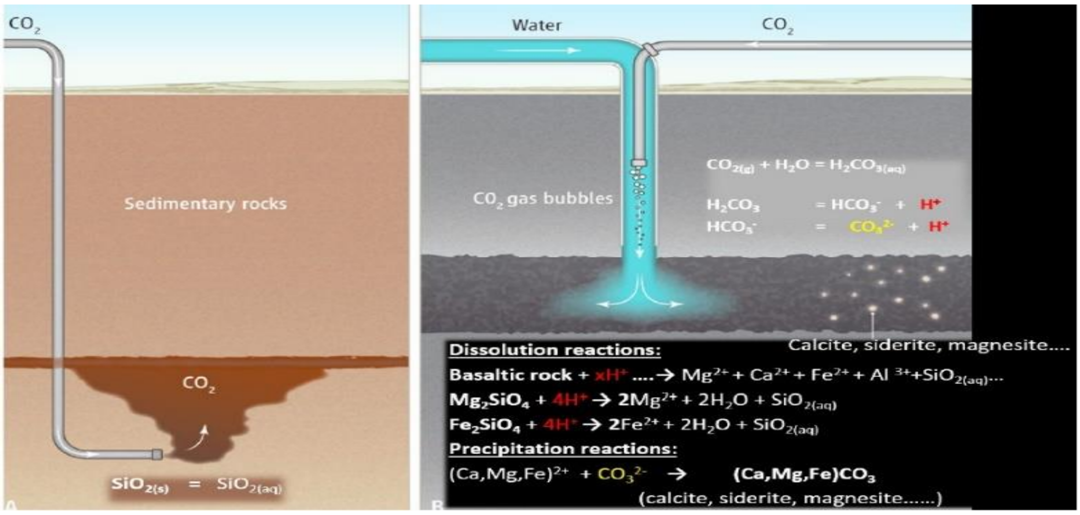

Figure 1 Schematic Process of Carbon Mineralization in the Basalts at Carbfix Pilot Injection Site, Iceland (Sigurdur R. Gíslason et al., 2018)

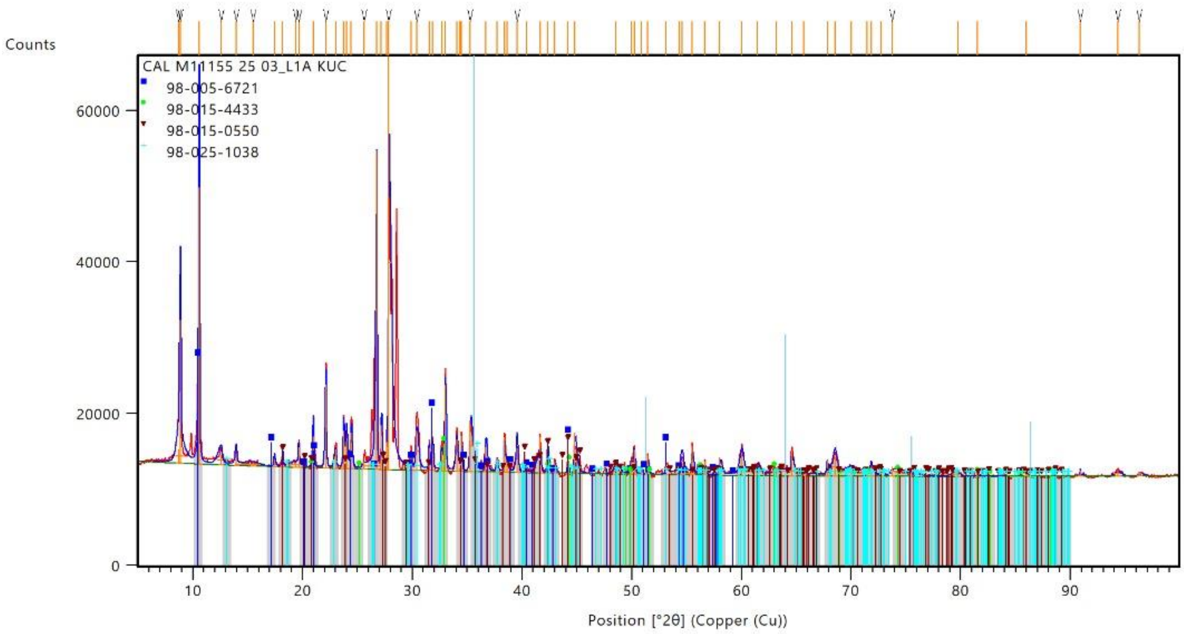

Figure 2 XRD Graph of the Sample collected near Sematan, Kuching, Eastern Malaysia

Conclusions

The Preliminary results obtained from the Geochemical, Geomechanical, and petrophysical experiments of the Kuantan area, Peninsular Malaysia and Sematan area, Eastern Malaysia Basalts suggest that the mineral compositions, morphology, characteristics, strength/integrity, natural fractures, and porous nature could yield the necessary potential for CO_2 Geo-sequestration study in the onshore basalts of Malaysia for long-term stability and for establishing a scalable storage model using Reactive Transport modelling simulations, which will enhance to develop a robust framework and techniques for CO_2 mineralization in the onshore mafic basalt formations of Malaysia.

However, the lack of deep thickness data of these basalt formations could limit further investigations of CO_2 sequestration potential by large pilot-scale studies in the future. Future research should rigorously focus by accessing various laboratory experiments and techniques from pore-core scale based on fluid-rock interaction studies, which could examine the CO_2 mineralization potential, reaction kinetics of the basalts found in Malaysia. The theoretical capacity estimation of CO_2 storage in these basalt formations should also be evaluated for further upscaling and tackling CO_2 emissions of Malaysia.

The development of basalt-based CO_2 sequestration aligns with Malaysia's carbon neutrality commitments and could complement existing forest-based carbon sequestration efforts. Research indicates that CO_2 sequestration in basalt will play an important role in creating a more sustainable future. The future looks promising for CO_2 sequestration in Malaysian basalts, particularly given the proven reactivity and the growing global emphasis on permanent carbon storage solutions. However, scaling from laboratory studies to commercial deployment will require significant investment in research, infrastructure, and regulatory frameworks specific to Malaysia's geological and environmental conditions.

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