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The Potential of CO_2 Sequestration from Basaltic Rock in Peninsular Malaysia
(Potensi Penyerapan CO_2 daripada Batuan Basaltik di Semenanjung Malaysia)

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ABSTRACT

Basaltic rock is a efficient for long-term solution in carbon dioxide (CO_2) sequestration because of its ability to chemically bind CO_2 in stable and form a solid mineral, which minimizes the risk of leakage and for permanent storage. This study investigates the mineralogy and geochemistry of Segamat and Kuantan basalts in Peninsular Malaysia to evaluate their suitability for mineral carbonation. Petrographic and mineralogical analyses indicate basalt contains silicate minerals, which are plagioclase (50-60)%, pyroxene (20-30)% and olivine (10-20)% that are highly conducive to CO_2 mineral carbonation. Calcite, magnesite, and siderite are expected to form carbonate minerals through chemical reactions. FESEM analysis shows that basaltic rocks have microcracks and micropores, which are tiny spaces within the rock. These structures provide pathways and space for CO_2 to flow and react with the rock, making it easier for the gas to be stored as solid carbonates. This porosity enhances CO_2 absorption and mineralization, improving the efficiency of carbon sequestration. The strategic location of Kuantan near seawater sources offers unlimited access during CO_2 injection activities. Both regions exhibit metaluminous properties that are compatible with a diverse range of mineral carbonation techniques. The Segamat and Kuantan basalts are ideal for CO_2 mineral carbonation due to their reactive silicate minerals, potential for carbonate formation (calcite, magnesite, siderite), and favorable microcrack structures. Their metaluminous, silica-undersaturated composition and Kuantan's proximity to water sources enhance their potential for effective CO_2 storage and mineralization.

Keywords: Carbon dioxide sequestration; Kuantan basalt; mineral carbonation; Segamat basalt

ABSTRAK

Batuan basal adalah berkesan untuk jangka panjang bagi pengasingan karbon dioksida (CO_2) kerana kemampuannya untuk menggabungkan CO_2 secara kimia dalam bentuk mineral pepejal yang stabil, yang meminimumkan risiko kebocoran dan memastikan penyimpanan yang kekal. Penyelidikan ini merangkumi aspek mineralogi dan geokimia basal dari Segamat dan Kuantan di Semenanjung Malaysia untuk menilai kesesuaian terhadap karbonasi mineral. Analisis petrografi dan mineralogi menunjukkan bahawa basal mengandungi mineral silikat, iaitu plagioklas (50-60)%, piroksen (20-30)% dan olivin (10-20)% yang sangat sesuai untuk karbonasi mineral CO_2. Kalsit, magnesit dan siderit dijangka terbentuk melalui reaksi kimia. Analisis FESEM menunjukkan bahawa batuan basal mempunyai mikro-retakan dan mikro-pori, yang merupakan ruang kecil dalam batu. Struktur ini menyediakan laluan dan ruang untuk CO_2 mengalir dan bertindak balas dengan batu, memudahkan gas disimpan sebagai karbonat pepejal. Kekosongan ini meningkatkan penyerapan CO_2 dan mineralisasi serta memperbaiki kecekapan pengasingan karbon. Lokasi strategik Kuantan yang dekat dengan sumber air laut menawarkan akses tanpa had semasa aktiviti suntikan CO_2. Kedua-dua kawasan menunjukkan sifat metaluminous yang serasi dengan pelbagai teknik karbonasi mineral. Basal Segamat dan Kuantan adalah sesuai untuk karbonasi mineral CO_2 kerana mineral silikat reaktif yang ada berpotensi untuk pembentukan karbonat (kalsit, magnesit, siderit) serta struktur mikro-retakan yang secara semula jadi ada. Komposisi metaluminous dan kekurangan silika serta jarak Kuantan dengan sumber air meningkatkan potensi mereka untuk penyimpanan dan mineralisasi CO_2 yang berkesan.

Kata kunci: Karbonasi mineral; Kuantan basal; penjerapan karbon dioksida; Segamat basal

INTRODUCTION

Climate change caused by greenhouse gaseous (GHGs) emissions poses a global threat to the earth-GHGs are derived from two primary sources: human activities and natural events (Nunes 2023). Examples of human activities contributing to CO_2 emissions are industrialization, electricity generation, transportation, deforestation and open burning, and agriculture (Gavurova, Rigelsky & Ivankova 2021; Tajuddin & Masseran 2023). These activities have increased CO_2 concentration in the atmosphere than usual and have been identified as a significant contributor to climate change. On the other hand, natural sources of CO_2

emissions include volcanic eruptions and natural forest fires. These events release large amounts of CO_2 into the atmosphere, causing climate abnormality and have far-reaching environmental implications that could exacerbate existing climatic conditions, which impact increasing global earth temperature, subsequently causing drought, coastal erosion, abnormal wind flow, and creating typhoons (Stocker et al. 2013). Much research has addressed this issue and is trying to reduce greenhouse gaseous emissions into the atmosphere by introducing advanced technology (Ghoshal & Zeman 2010; Lee et al. 2023; Ye et al. 2022). Therefore, an effective measure must be taken to combat climate change for the betterment of future generations.

Carbon capture and storage emerge as viable solutions to address this issue. Hence, identifying secure CO_2 storage sites represents one of our era's most pressing scientific predicaments. Injection of CO_2 into basaltic formations offers significant benefits, including permanent mineralization-based storage and ample potential storage capacity (Gislason & Oelkers 2014; McGrail et al. 2006; Snaebjornsdottir et al. 2014). Basaltic rocks possess abundant divalent cations such as Ca^{2+}, Mg^{2+}, and Fe^{2+}, which are released by the CO_2-charged water that facilitates the formation of stable carbonate minerals such as calcite ($CaCO_3$), magnesium ($MgCO_3$), and siderite ($FeCO_3$) suitable for long-term CO_2 sequestration purposes (Gislason & Oelkers 2014; Gislason et al. 2014, 2010; Oelkers, Gislason & Matter 2008; Snaebjornsdottir et al. 2014).

The initial stage of CO_2 dissolution is a crucial aspect that occurs universally in all types of minerals present in basalt during the carbonation process. These preliminary stages establish a foundation for subsequent reactions and mineral transformations. The introduction of CO_2 into basalt formations can be accomplished through direct injection or by dissolving it in water before injecting it. This procedure commences with the dissolution of CO_2 in water, resulting in the development of carbonic acid, as in chemical reaction (1) (Rasool & Ahmad 2023). Various mineral assemblages in basaltic rock may undergo carbonation reactions. Chemical reactions in overall olivine carbonation (2), overall pyroxene carbonation (3), and overall plagioclase carbonation (4) exemplify the overall process (Rasool & Ahmad 2023).

$$\begin{gathered} CO_{2\,(g)} + H_2O_{\,(l)} \dashrightarrow H_2CO_{3\,(l)} \\ H_2CO_{3\,(aq)} \dashrightarrow H^+_{\,(aq)} + HCO_3^{\;-}{}_{(aq)} \end{gathered} \tag{1}$$

$$\begin{gathered} (Mg,Fe)_2SiO_4 + 2CO_{2\,(g)} + H_2O_{\,(l)} \rightarrow 2(Mg,Fe) \\ CO_{3\,(s)} + SiO_2\cdot H_2O_{\,(s)} \end{gathered} \tag{2}$$

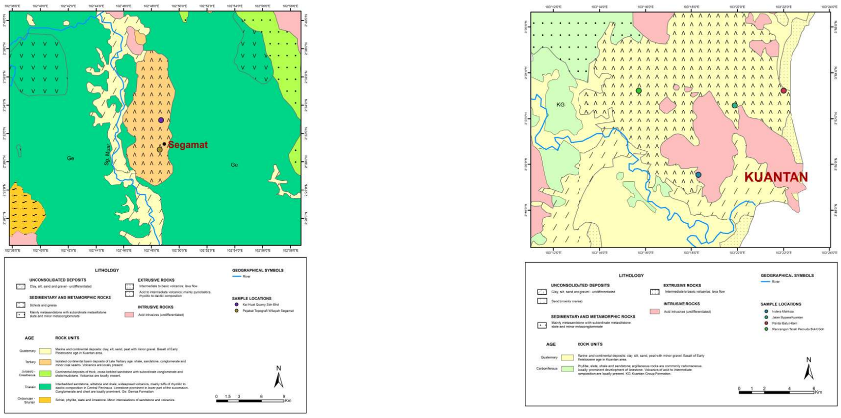
$$\begin{gathered} 3(Mg,Fe,Ca)(Si,Al)_2O_{6\,(s)} + 3CO_{2\,(g)} + 8H_2O_{\,(l)} \\ \rightarrow 3(Mg,Fe,Ca)CO_3 + Al_2O_3\cdot 2H_2O_{\,(s)} + \\ 6SiO_2\cdot H_2O_{\,(s)} \end{gathered} \tag{3}$$

$$\begin{gathered} (Na,Ca)(Al,Si)\,AlSi_2O_{8\,(s)} + CO_{2\,(g)} + H_2O_{\,(l)} \\ \rightarrow CaCO_{3\,(s)} + NaHCO_{3\,(aq)} + Al_2O_3\cdot H_2O_{\,(s)} \\ + SiO_{2\,(s)} \end{gathered} \tag{4}$$

This study evaluates basaltic rocks to assess their suitability for geological carbon storage. This investigation analyses the petrological and geochemical traits required to apply mineral carbonation to this formation.

GEOLOGICAL SETTING BASALTS IN PENINSULAR MALAYSIA

Grubb (1965) classified Segamat basalt (Figure 1(a)) as potassium-rich lava, initially thought to be contemporaneous



(a) (b)

FIGURE 1. (a) Geological map of Segamat, Johor, and (b) Geological map of Kuantan, Pahang. Both maps show the basaltic rocks' sampling location (Ng, Tate & Tan 2008)

with Kuantan basalt, which is categorized as alkali-rich lava (Chakraborty 1977; Fitch 1951; Ghani & Taib 2007; Haile 1983). Based on K-Ar dating techniques employed by Bignell and Snelling (1977), these rocks are considered the youngest in the region, indicating their age to be at least early Paleocene with an average age of 62 +/- 0.2 Ma. Basaltic lavas in Kuantan were mapped and analyzed by Fitch (1951). The Kuantan region has vast basaltic lavas occupying approximately 125 km^2 (Figure 1(b)). They are the youngest rocks in the region, with an average age of 1.7 +/- 0.2 Ma based on K-Ar dating techniques employed by Haile et al. (1983). Fitch (1951) suggested Bukit Tinggi as the origin of basaltic lava near Kuantan, flowing in various directions based on topography. Raj (1990) proposed another vent 1.9 km northwest called Bukit 212, which erupted earlier than Bukit Tinggi's lava flows. Kuantan Basalt has two types of lava flow: alkali olivine basalt and basanite (Fitch 1951; Haile 1975). Chemical analyses showed that it has two distinct magma types: alkali olivine basalt magma and olivine nephelinite magma (Chakraborty 1977; Ghani & Taib 2007). The western part mainly comprises of olivine basalts, while the eastern part is limited to olivine nephelinites (Ghani & Taib 2007). Mineral carbonation may occur based on the rock composition of Segamat and Kuantan.

MATERIALS AND METHODS

A total of 24 samples of basaltic rocks were collected from Kuantan and Segamat and prepared into thin sections for petrographic analysis. Microscopic examination was done using Olympus BX43F microscopes, facilitating the identification of minerals and textural components. X-ray diffraction (XRD) analysis was employed at i-CRIM Laboratory Universiti Kebangsaan Malaysia to identify mineral phases in basalt samples. The samples were crushed to powder, dried and analyzed using BRUKER-binary V4 equipment with a 0.0250 step size °2Th ranging from 20.0000° to 79.9750° under a generator setting of 40 mA and 40 kV. Mineral identification and quantification were done using Highscore software by Malvern Panalytical. Field Emission Scanning Electron Microscopy (FESEM) was used to identify surface roughness and grain morphology, where elemental composition was detected using Energy-dispersive X-ray spectroscopy (EDX). The primary element composition was analyzed at Bureau Veritas in Vancouver using X-ray fluorescence (XRF). The XRF analysis employs OREAS 184 certified reference material.

RESULTS

PETROGRAPHY ANALYSIS

Petrographic analysis of basalt rock samples from Segamat and Kuantan localities indicates a semicrystalline or microcrystalline texture consisting of crystalline and glassy materials (Figures 2 & 3). Due to their fine-grain size, these rocks were classified as fine-grained or aphanitic. The Segamat basalt (Figure 2(a) to 2(d)) exhibited pyroxene minerals belonging to the clinopyroxene group. Additionally, the orthopyroxene group was observed in both the Segamat basalt (Figure 2(c) and 2(d)) and Kuantan basalt (Figure 3(a) & 3(c)). The olivine mineral group is displayed in the Kuantan basalt (Figure 3(a) to 3(c)). Plagioclase feldspar in both basalts form as a groundmass (Figures 2(a) & 2(c) & Figure 3(b) & 3(d)). Furthermore, sericite and chlorite have been identified as an alteration mineral within the Segamat basalt (Figure 2(b)). Sericite commonly forms as an alteration product of plagioclase and alkali feldspars. Chlorite is a standard alteration product of mafic minerals like pyroxenes and olivine when interacting with hydrothermal fluids or undergoing low-grade metamorphism (Deer, Howie & Zussman 1992; Gifkins, Herrmann & Large 2005). The Kuantan basalt (KNT3 and KNT7) displayed an intergranular texture, as shown in Figure 3(d).

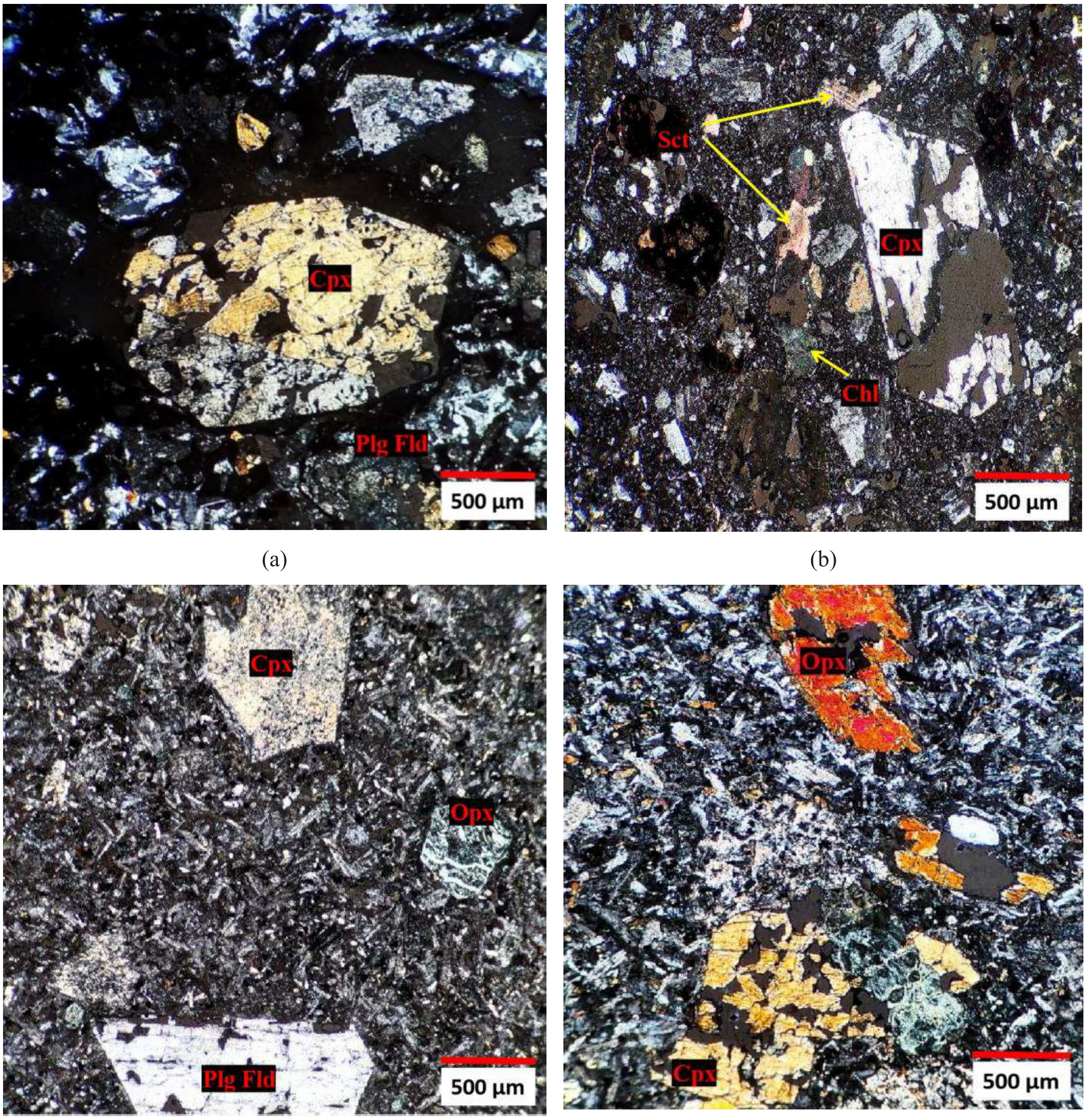
The mineralogical composition of both Segamat and Kuantan is primarily composed of phenocrysts with diameters that span from 100 μm to 700 μm, mainly comprising pyroxene (20%-30%) and olivine (10%-20%) groups that exhibited euhedral to subhedral shapes. Plagioclase feldspar was mainly formed as groundmass at approximately 50% - 60% of the total mineral composition, while potassium feldspar was present only in trace amounts between 3% and 5%. Quartz, calcite, chlorite, sericite, and opaque minerals are accessory (<1%) in the Segamat and Kuantan Basalt.

XRD ANALYSIS

An XRD analysis identified the mineralogical composition of the Segamat and Kuantan basalt samples. Both basalts comprise several mineral groups: plagioclase feldspar, pyroxene, and olivine. The minerals identified in Segamat basalt (Figure 4(a)) are anorthite, bytownite, labradorite, andesine (plagioclase feldspar), enstatite (orthopyroxene), augite and diopside (clinopyroxene). In comparison, the minerals identified in Kuantan basalt (Figure 4(b)) are anorthite, bytownite, labradorite, andesine (plagioclase feldspar), enstatite, (orthopyroxene), augite and diopside (clinopyroxene) and forsterite (olivine). The mineral with highest peak intensity for Segamat basalt are anorthite (Pos. [°2Th.] 27.96) and bytownite (Pos. [°2Th.] 27.52), while in Kuantan basalt are augite (Pos. [°2Th.] 29.85), anorthite (Pos. [°2Th.] 27.80) and diopside (Pos. [°2Th.] 30.29).

FESEM WITH EDX SPECTROSCOPY ANALYSIS

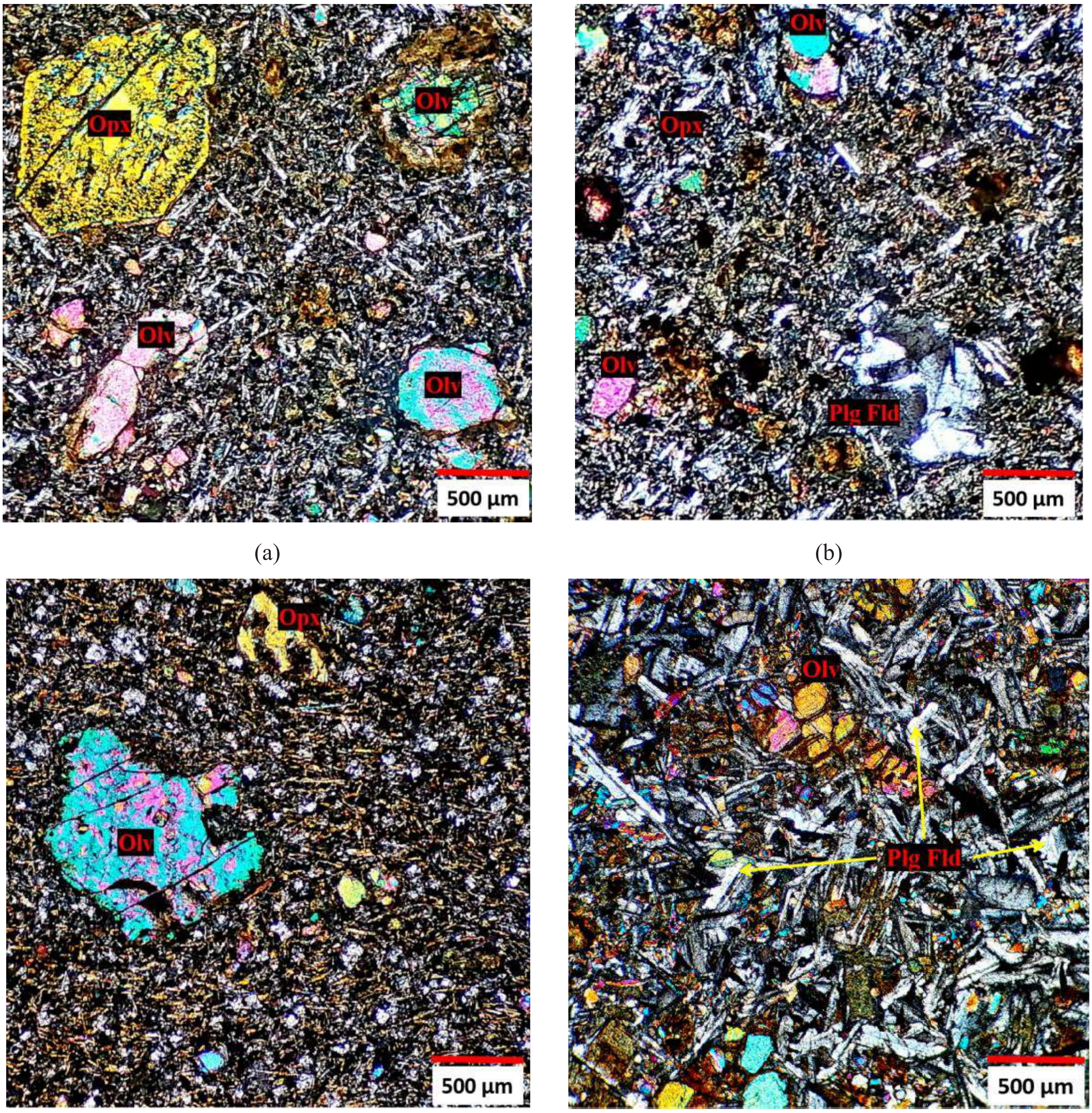
FESEM photos from Segamat and Kuantan basalt are given in Figure 5(a) and 5(c), respectively. Upon examination of these photos, the voids and fissures can be identified as distinct black areas. The basaltic rock contains various minerals, mainly plagioclase feldspar, pyroxene, and



(a) (b)

(c) (d)

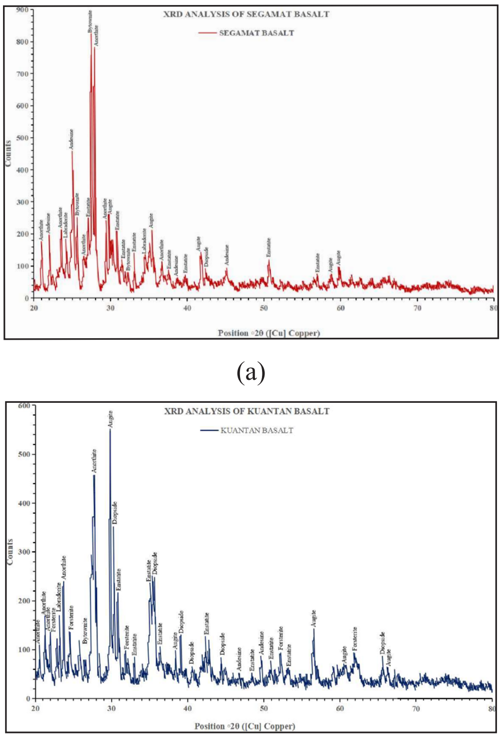
FIGURE 2. Petrography of Segamat basalt samples under cross nicol using objective Plsn N 4×/0.10 P ∞ / - /FN22. Photomicrograph shows Segamat basalt formed as porphyritic texture with (Cpx) clinopyroxene (a-d), (Opx) orthopyroxene (c-d) and (Plg Fld) plagioclase feldspar (c) as phenocryst enclosed by microcrystalline groundmass. Alteration minerals (b) found are (Sct) sericite and (Chl) chlorite



(a) (b)

(c) (d)

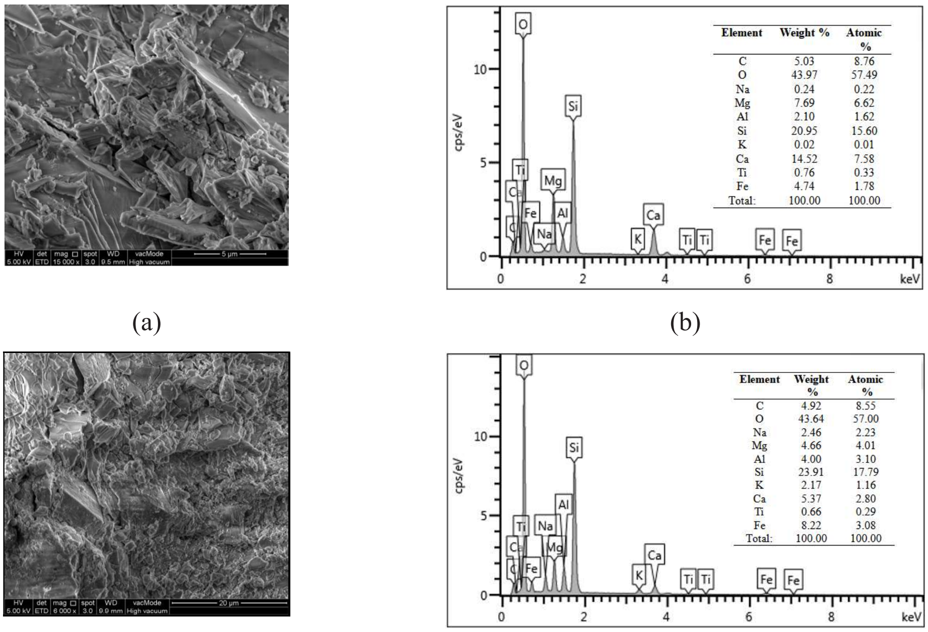
FIGURE 3. Petrography of Kuantan basalt samples under cross nicol using objective Plsn N 4×/0.10 P ∞ / - /FN22. Photomicrograph shows Kuantan basalt formed as porphyritic texture with (Olv) olivine (a-d), (Opx) orthopyroxene (a-c), and (Plg Fld) plagioclase feldspar (b,d) as phenocryst enclosed by microcrystalline groundmass



(a)

(b)

FIGURE 4. (a) XRD analysis of the Segamat basalt, and (b) XRD analysis of the Kuantan basalt



Element	Weight %	Atomic %
C	5.03	8.76
O	43.97	57.49
Na	0.24	0.22
Mg	7.69	6.62
Al	2.10	1.62
Si	20.95	15.60
K	0.02	0.01
Ca	14.52	7.58
Ti	0.76	0.33
Fe	4.74	1.78
Total:	100.00	100.00

Element	Weight %	Atomic %
C	4.92	8.55
O	43.64	57.00
Na	2.46	2.23
Mg	4.66	4.01
Al	4.00	3.10
Si	23.91	17.79
K	2.17	1.16
Ca	5.37	2.80
Ti	0.66	0.29
Fe	8.22	3.08
Total:	100.00	100.00

(a) (b)

(c) (d)

FIGURE 5. (a) to (b) FESEM photo with E.D.X. spectrum of Segamat basalt sample. (c) to (d) FESEM photo with E.D.X. spectrum of Kuantan basalt sample C: Carbon; O: Oxygen; Na: Sodium; Mg: Magnesium; Al: Aluminium; Si: Silica; K: Potassium; Ca: Calcium; Ti: Titanium; Fe: Ferum

olivine groups, with many intergranular pores and microcracks mainly distributed around the mineral. At a great magnification of 15,000× of Segamat basalt (Figure 5(a)) and 6,000× of Kuantan basalt (Figure 5(c)), highly porous and micropores can be observed in these basaltic rock formations. According to the E.D.X. spectrum analysis (Figure 5(b) & 5(d)), Segamat and Kuantan basalts are mainly composed of O, Si, Ca, Mg, Fe, C, Al, Ti, Na, and K. The six most significant values of the elements detected in Segamat basalt are O, Si, Ca, Mg, C, and Fe, while in Kuantan basalt, it is O, Si, Fe, Ca, C, and Mg. According to the E.D.X. spectrum analysis, the total weight percentages of Ca, Mg, and Fe for both Segamat and Kuantan basalts are 26.95 wt% and 18.25 wt%, respectively.

X-RAY FLUORESCENCE (XRF) ANALYSIS

Table 1 shows an overview of the significant oxides found in the Segamat and Kuantan basalts by XRF analysis. The Segamat basalt has a range of Fe_2O_3 (7.73-9.19 wt%), MgO (3.64-7.68 wt%), and CaO (6.19-8.88 wt%). In comparison, the chemical composition of Kuantan basalt comprises Fe_2O_3 (11.79-15.53 wt%), MgO (4.53-9.60 wt%), and CaO (7.26-10.99 wt%). According to the Total Alkali-Silica (TAS) diagrams by Middlemost (1994) (Figure 6(a)), Segamat basalt was characterized as a basaltic trachyte-andesite, while Kuantan basalt was plotted on the wide range of rock type classifications, namely as tephrite, trachy basalt and basalt. In the Alkali, Iron and Magnesium (AFM) discrimination plot of Irvine and Baragar (1971), Basalt samples from both Kuantan and Segamat are plotted in calc-alkaline series, except for KNT2 and KNT6 from Kuantan are plotted in tholeiite series (Figure 6(b)). However, further classification based on the potassium enrichment showed that Segamat basalt was plotted on the shoshonite affinity (Figure 6(c)) (Peccerillo & Taylor 1976). This is slightly different for the Kuantan basalt, where the data was plotted on the calc-alkaline series but in the variation of medium to high potassium (Figure 6(c)). The K/(Na+K)-B diagram by Debon and Le Fort (1983) was used for both areas to differentiate between potassic and sodic associations. Segamat basalt has a different association with Kuantan, where potassic is dominated by basalt from Segamat, while sodic is dominated by Kuantan basalt (Figure 6(d)). Based on the alumina (Al_2O_3) saturation, both Segamat and Kuantan basalt show a metaluminous affinity (Figure 6(e)) (Shand 1943).

DISCUSSION

SUITABILITY OF SEGAMAT AND KUANTAN BASALTS FOR CO_2 MINERAL CARBONATION POTENTIAL

The CO_2 mineral carbonation in basaltic rock formation is primarily attributed to its mineralogy and geochemistry, which play a main role in facilitating the process. There have been several studies in this particular area to determine a few basaltic types that are suitable to serve as hosts for CO_2 mineral carbonation storage (Alfredsson et al. 2013; Ayub et al. 2020; Dessert et al. 2003; Gislason et al. 2014, 2010; Koukouzas et al. 2019; Mcgrail et al. 2006; Rasool & Ahmad 2023; Rosenbauer et al. 2012; Schaef, McGrail & Owen 2010).

In the petrography analysis, both Segamat and Kuantan basalts (Figures 2 & 3) show the main mineral assemblages for the mineral carbonation process, which are plagioclase feldspar, pyroxene, and olivine groups. Among these mineral groups, plagioclase feldspar is the dominant, followed by pyroxene and olivine. These minerals indicate that the basalt rock formation in these study areas has an abundance of Ca, Fe, and Mg-bearing minerals. Based on this microscopic analysis, the XRD analysis identified mineralogical elements in the basalts. According to the group of plagioclase feldspar, the Segamat and Kuantan basalts consist of anorthite, bytownite, labradorite and andesine minerals.

The next most abundant group of minerals is pyroxene. Both clinopyroxene and orthopyroxene are present in Kuantan and Segamat Basalt. The Segamat and Kuantan basaltic clinopyroxene mainly comprises diopside and augite, which crystallizes in a monoclinic structure. Orthopyroxene, which crystallized as an orthorhombic in the Segamat and Kuantan basalts as a enstatite. The olivine group in Kuantan basalt is forsterite, a magnesium-rich end-member of the olivine solid solution series. The Segamat and Kuantan basalts effectively sequester CO_2 due to the presence of key minerals such as plagioclase feldspar, pyroxene and olivine. These minerals provide essential elements of calcium and magnesium to reacts with CO_2 to form stable carbonate.

An innovative approach, combining FESEM with EDX, enabled the existence of the microcracks, pores, and elemental composition of the basaltic rock in Segamat and Kuantan (Figure 5(a) & 5(c)). Pores and vesicles in basaltic rocks are highly significant for mineral carbonation, which involves converting CO_2 into solid carbonate minerals (Callow et al. 2018). These pores and vesicles provide an increased surface area for reaction with CO_2, enhance permeability and fluid flow through the rock matrix, expose reactive minerals like calcium-rich plagioclase feldspar, olivine, and pyroxenes to the CO_2, and offer reactive surface sites for carbonate mineral precipitation (Taksavasu et al. 2024). The EDX spectrum (Figure 5(b) & 5(d)) shows that the Segamat and Kuantan basalts consist of O, Si, Ca, Mg, Fe, C, Al, Ti, Na, and K in descending order. The total weight percentages of Ca, Mg, and Fe for both Segamat and Kuantan basalts are 26.95 wt% and 18.25 wt%, respectively.

Based on the XRF analysis, on average, the Segamat basalt consists of Fe_2O_3 (8.42 wt%), MgO (6.02 wt%), and CaO (7.69 wt%), while the Kuantan basalt consists of Fe_2O_3 (13.48 wt%), MgO (7.76 wt%), and CaO

TABLE 1. Major oxides geochemistry of the basaltic rocks. SGMT: Segamat Basalt; KNT: Kuantan Basalt

Major oxide / Sample	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	LOI
SGMT 1	50.63	14.92	8.08	7.58	6.83	2.74	4.28	1.01	0.65	0.15	2.20
SGMT 2	50.58	15.49	8.07	6.39	7.61	2.01	5.46	1.04	0.66	0.14	2.60
SGMT 3	50.95	14.64	8.16	5.95	8.76	2.12	5.45	1.04	0.68	0.11	2.00
SGMT 4	51.26	14.99	7.73	5.71	8.79	2.08	5.27	1.00	0.61	0.12	2.50
SGMT 5	51.22	15.10	8.31	7.68	6.91	2.78	4.37	1.04	0.67	0.15	2.30
SGMT 6	50.77	15.60	8.16	6.46	7.59	1.99	5.44	1.05	0.67	0.15	2.60
SGMT 7	51.23	14.80	8.32	5.98	8.74	2.13	5.50	1.06	0.69	0.12	2.10
SGMT 8	51.42	14.96	7.75	5.78	8.88	2.11	5.27	1.01	0.61	0.12	2.70
SGMT 9	49.88	15.15	9.19	6.87	6.76	3.06	4.59	0.97	0.56	0.16	3.40
SGMT 10	50.30	17.27	8.50	3.71	8.18	2.1	5.56	1.07	0.76	0.20	2.60
SGMT 11	51.00	15.98	8.49	5.38	6.19	2.87	5.12	1.05	0.66	0.18	2.50
SGMT 12	49.84	15.47	8.77	6.37	8.19	2.1	4.92	1.05	0.64	0.18	2.90
SGMT 13	49.65	15.04	9.12	6.85	6.73	3.05	4.56	0.96	0.55	0.16	3.80
SGMT 14	50.06	17.22	8.39	3.64	8.11	2.09	5.53	1.06	0.76	0.20	2.20
SGMT 15	51.30	15.95	8.81	5.68	6.57	2.83	5.09	1.07	0.67	0.19	2.40
SGMT 16	49.95	15.51	8.82	6.34	8.21	2.11	4.94	1.05	0.64	0.17	2.80
KNT 1	40.98	12.32	14.53	9.28	10.99	4.29	1.83	2.45	1.12	0.21	2.6
KNT 2	46.7	14.22	15.53	4.53	8.3	2.9	1.02	2.91	1.18	0.25	2.3
KNT 3	50.65	14.33	11.79	7.71	7.26	3.57	1.33	1.75	0.36	0.14	1.7
KNT 4	47.07	13.65	12.09	9.55	8.58	3.66	1.56	1.84	0.79	0.18	1.6
KNT 5	40.85	12.42	14.42	9.19	10.83	4.25	1.83	2.43	1.13	0.21	2.7
KNT 6	47.03	14.36	15.48	4.54	8.36	2.93	1.03	2.93	1.16	0.25	2.4
KNT 7	50.76	14.35	11.81	7.71	7.29	3.58	1.32	1.75	0.36	0.14	1.7
KNT 8	46.93	13.58	12.16	9.6	8.58	3.65	1.57	1.84	0.78	0.18	1.8

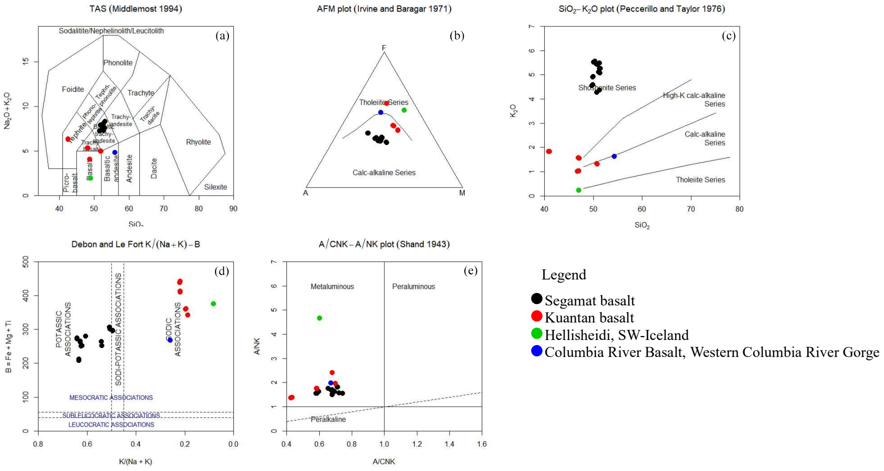


FIGURE 6. (a) T.A.S. by Middlemost (1994), (b) A.F.M. plot by Irvine and Barage (1971). (c) SiO_2-K_2O plot by Peccerillo and Taylor (1976). (d) K/(Na+K)-B plot by Debon and Le Fort (1983), and (e) A/CNK-A/NK plot by Shand (1943)

(8.77 wt%). Theoretically, the maximum CO_2 sequestration capacity using a density of CO_2 at Standard Temperature and Pressure (STP) (0.0019 g/cm³) for Segamat basalt and Kuantan basalt is approximately 9.1 L and 12.0 L of CO_2 per unit mass of the rock. To compare with other areas, the basalt from Hellisheidi, SW-Iceland, and Columbia River Basalt, Western Columbia River Gorge, was chosen (Alfredsson et al. 2013; Yuh, Evarts & Conrey 2022). These two areas have been known to have been established for CO_2 mineral carbonation through basaltic rock formation. XRF data provided in Hellisheidi, SW-Iceland, shows the average of Fe_2O_3 (13.63 wt%), MgO (7.23 wt%), and CaO (11.12 wt%) (Alfredsson et al. 2013). While in the Columbia River Basalt, Western Columbia River Gorge shows that the Fe_2O_3 (11.83 wt.%), MgO (3.76 wt.%), and CaO (7.40 wt.%) (Yuh, Evarts & Conrey 2022). Theoretically, the maximum CO_2 sequestration capacity using a density of CO_2 at STP (0.0019 g/cm³) for Hellisheidi and Columbia River Basalt is approximately 12.7 L and 8.6 L of CO_2 per unit mass of the rock, respectively.

The Segamat basalt samples plotted in the basaltic trachyte-andesite field on the TAS diagram (Figure 6(a)) indicate an intermediate composition between basaltic and trachytic/andesitic affinities. This classification suggests that the Segamat basalt magma may have undergone moderate degrees of fractionation or evolved from a more primitive basaltic composition. Alkali feldspar or enrichment in alkali elements could contribute to the elevated total alkali content, shifting the composition towards the trachytic/andesitic fields. In contrast, the Kuantan basalt samples exhibited a more comprehensive range of rock type classifications on the T.A.S. diagram, spanning from tephrite and trachy basalt to basalt (Figure 6(a)). This diverse distribution reflects the heterogeneous nature of the Kuantan basalt magma system and potentially varying degrees of magmatic evolution or fractionation processes.

Segamat and Kuantan basalts have a magma-calc-alkaline series (Figure 6(b)). However, further classification based on the potassium enrichment showed that Segamat basalt was plotted on the shoshonite affinity (Figure 6(c)). This basalt is slightly different from the Kuantan basalt, where the data is plotted on the calc-alkaline series but in the variation of medium to high potassium (Figure 6(c)). The effect of potassium enrichment in basalt on mineral carbonation has been studied, and it has been found that potassium can play a significant role in enhancing the carbonation process. Minerals: Several findings show that potassium can promote the dissolution of silicate minerals, enhance the formation of carbonate minerals, and improve the kinetics of the carbonation reaction in term of how quickly CO_2 can react with reactive minerals to form solid carbonates (Declercq, Bosc & Oelkers 2013; Gerdemann et al. 2007; Sanna et al. 2014).

Regarding potassic and sodic associations, Segamat basalt has been dominated by potassic, while sodic is dominated by Kuantan basalt and two other reference studies (Figure 6(d)). Typically, the tholeiite basalts are more sodic when compared with the calc-alkaline basalt, which is more potassic. Even though both magma series are viable for mineral carbonation, tholeiite is the most expected to dominate reactivity due to the higher plagioclase feldspar, pyroxene, and olivine groups. However, based on the alumina (Al_2O_3) saturation, both Segamat and Kuantan basalt show a metaluminous affinity (Figure 6(e)), which indicates higher divalent cations bound in minerals like plagioclase, pyroxene, and olivine are typically more reactive in mineral carbonation reactions.

This paragraph provides an in-depth discussion on the potential of utilizing basaltic rocks for mineral carbonation, as explored in this study. The detailed characterization of basaltic rocks from the Segamat and Kuantan regions of Peninsular Malaysia through petrographic, FESEM-EDX, XRD, and XRF analyses have shown their promising potential for mineral carbonation and long-term CO_2 sequestration. The high abundance of reactive silicate minerals like plagioclase (50-60%), pyroxene (20-30%), and olivine (10-20%) identified through petrography provides a mineralogical composition highly amenable to carbonation reactions. The microporous and microcracked textures observed under FESEM offer an ideal high-surface-area microstructure that facilitates effective CO_2 diffusion and carbonation. XRD results confirm the silica-undersaturated nature of these basalts, which is a requisite for promoting extensive carbonation. Complementary XRF data on the bulk chemical compositions, notably the significant concentrations of divalent cations like Ca, Mg, and Fe, indicate a high capacity for forming desirable carbonate minerals like calcite, magnesite, and siderite as permanent CO_2 traps. Moreover, the strategic location of Kuantan, proximal to seawater sources, enables access to unlimited low-cost water required for enhanced carbonation processes. Collectively, the convergence of favourable mineralogy, microstructure, bulk chemistry, and abundant aqueous resources establishes the Segamat and Kuantan basalts as exceptional feedstocks for both *in-situ* and *ex-situ* mineral carbonation approaches aimed at efficient and secure long-term CO_2 storage and mitigation of anthropogenic emissions.

CONCLUSION

Segamat and Kuantan basalt possess silicate minerals highly conducive to CO_2 mineral carbonation. The presence of reactive minerals such as (1) Plagioclase feldspar: anorthite, bytownite, labradorite, and andesine; (2) Pyroxene: diopside and augite; and (3) Olivine: forsterite suggest that the basaltic rock is favourable for mineral carbonation. Based on data availability from the analyses conducted on both Segamat and Kuantan basalts, calcite ($CaCO_3$), magnesite ($MgCO_3$), and siderite ($FeCO_3$) are likely carbonate minerals to form. In addition, the formation of microcracks and pores in the rocks also makes an ideal condition for CO_2 storage or *ex-situ* mineral carbonation feedstock. Kuantan basalt is strategically located for mineral carbonation due to its proximity to the sea, which provides unlimited water resources during CO_2 injection. Both areas are undersaturated, metaluminous with silica undersaturated, and suitable for mineral carbonation processes. In summary, the Segamat and Kuantan basalts hold the potential for adequate CO_2 storage through their ability to undergo *ex-situ* mineralization feedstock or direct injection of CO_2 into geological formations.

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