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Characteristic Analysis of Indonesian Low and Medium Rank Coals and Their Influence on Carbon Dioxide Adsorption Capacity

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Abstract - Indonesia has great deep-seated coal potential , such as Lakat coal and Muaraenim coal, which can be utilized as a medium for Carbon Capture and Storage (CCS). These coals vary in characteristic which affects their ability to adsorb or store carbon dioxide gas (CO_2). The moisture content of the Lakat coal is less than that of the Muaraenim coal, while the ash content of Lakat coal is 4-5 times higher than the Muaraenim coal. Lakat coal contains more vitrinite content than Muaraenim coal, while Muaraenim coal contains more inertinite content than Lakat coal. The CO_2 gas adsorption capacity of Muaraenim coal is 37.62 cc/g which higher than Lakat coal (31.56 cc/g) on dry ash-free basis. The adsorbed CO_2 is negatively correlated with vitrinite reflectance, ash content, and moisture content in both coals. The correlation between maceral composition (vitrinite and inertinite content) and adsorbed CO_2 content differs between these coals. These analyses will support the CCS/CCUS study in deep seated coal seams by providing the information of CO_2 maximum holding capacity in coal and their relationship to its chemical and organic composition.

Keywords: CO_2 adsorption capacity, organic composition, chemical composition, Lakat coal, Muaraenim coal

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INTRODUCTION

The use of fossil energy on industrial and individual scales will contribute to greenhouse gas emissions. The Paris Agreement, signed by 171 countries, including Indonesia, aims to limit the global average temperature increase to below 2°C above pre-industrial levels and strive to keep it within 1.5°C. Under this agreement, Indonesia also aims to achieve zero carbon emissions by 2060. Carbon capture and storage technology which provides geological storage options such depleted oil and gas reservoir, deep saline formation, deep unmineable coal seam, and basal formation is considered to be an effective strategy to achieve the net zero emission (Aminu *et al.*, 2017).

Deep unmineable coal seam becomes one of the attractive options, because the injected CO_2 into coal seams can also increase coalbed methane production (ECBM) (Talapatra, 2020). Geologically, Indonesia has great potential of deep unmineable coal seam, around 43 billion tons (CMCGR, 2020). One method of identifying the potential of coal as a carbon dioxide gas storage medium is through the analysis of the CO_2 adsorption isotherm. Some studies that have analyzed the capability of CO_2 adsorption isotherm in Indonesian coal were carried out by Moore *et al*. (2014) and Tambaria *et al*. (2023). Their researches need to pay more attention to the relationship between the CO_2 adsorption capacity and coal chemical and organic characteristics.

Safei-Farouji *et al*. (2023) stated that several internal and external factors affected the CO_2 adsorption capacity in coal, including coal rank, moisture and ash content, pore structure, maceral composition, formation temperature, swelling, pressure, and gas type. This study aims to address the gap in understanding how these factors, such chemical and organic composition, specifically influence the CO_2 adsorption capacities of the Indonesian coal, especially Lakat and Muaraenim coals which differ in their coal rank. The coal samples were taken in Sungai Akar area, Indragiri Hulu Regency, Riau Province and Musi Banyuasin Regency, South Sumatera Province (Figure 1). This study is expected to be useful to identify the potential of CCS on coal by providing data and information on the CO_2 content in coal and the characteristics of coal which potential for storing CO_2.

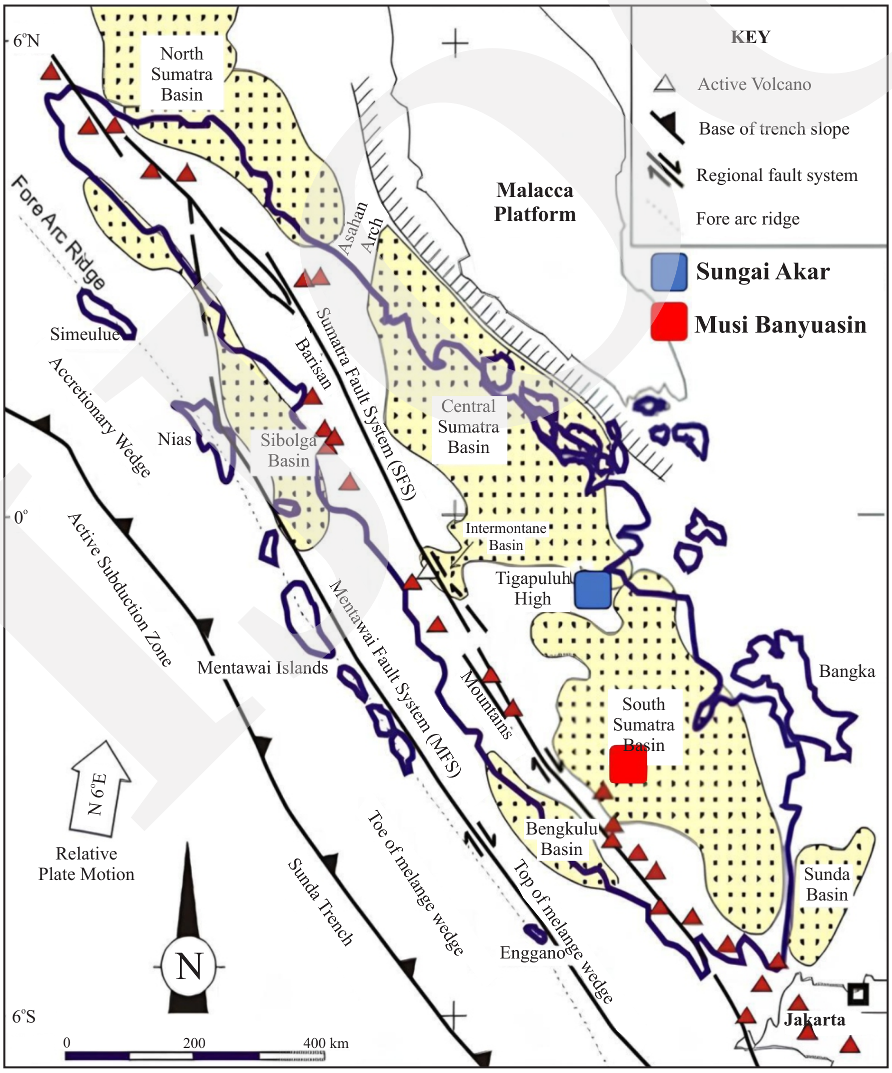

Figure 1. Study location on Sungai Akar Area (Blue Square) and Musi Banyuasin (Red Square) (Modified from Darman and Sidi, 2000).

Methods and Materials

Outcrop samples were collected from specific locations in Sungai Akar and Musi Banyuasin areas. Samples were selected based on stratigraphic positions and coal seam thickness . Coal samples from Sungai Akar area were collected from Lakat Formation which is Oligo-Miocene in age, while Musi Banyuasin samples were taken from Late Miocene Muaraenim Formation (Figure 2). A total of seven coal samples were analyzed, where three samples taken from the Sungai Akar area and four samples from the Musi Banyuasin area. Several laboratory analyses were conducted, including proximate, ultimate, petrography, calorific value, and CO_2 adsorption isotherm analyses. The proximate, ultimate, calorific value, and petrography analyses were conducted in CMCGR (Center for Mineral Coal and Geothermal Resources Laboratory) Bandung, while CO_2 adsorption isotherm analysis was performed in Energy Resources Consulting Pty. Ltd. in Queensland, Australia.

Proximate and Ultimate Analyses

Proximate analysis includes moisture, ash, volatile matter, and fixed carbon contents, while ultimate analysis includes carbon, hydrogen, nitrogen, and sulfur contents. The moisture value obtained from proximate analysis was measured as mass loss from a sample under specified conditions after heating in an oven. Ash yield was measured to determine how much material remains (called ash residue) after a lump of coal was combusted. Volatile matter is a measure of the nonwater gases formed from a coal sample during heating in absence of oxygen. Fixed carbon measured the amount of nonvolatile carbon remaining in a coal sample. It is a calculated value determined from other parameters measured in a proximate analysis (Kentucky Geological Survey, 2024). Calorific value analysis measured the heating ability of a coal and was needed to estimate the amount of coal needed to produce a desired amount of heat. The analysis was performed under ASTM D5865-19 (2019) as the standard. Calorific value was also used to define coal rank in low and medium rank coals according to the ASTM classification system (ASTM D388-15, 2002). The proximate analysis used ASTM D7582-15 (2023) as the standard.

The ultimate analysis provided a convenient method for reporting coal major organic elemental composition. For this analysis, a coal sample was combusted in an ultimate analyzer, which measured the weight percent of carbon, hydrogen, nitrogen, sulfur, and ash from a coal sample (Speight, 2015). The total carbon, hydrogen, and nitrogen were determined simultaneously from the same sample in the analyzer. The total oxygen was calculated from the other values. These analyses supported the chemical composition from proximate analyses, especially moisture and fixed carbon content, which influenced carbon dioxide content. The ultimate analysis used ASTM D5373-21 (2021) as the standard.

Organic Petrography Analysis

Petrography analysis determines the organic (maceral) and inorganic (mineral matter) constituent. Macerals are the altered remains and byproducts of the original plant material from which the coal-forming peat originated. There are three maceral groups: vitrinite, inertinite, and liptinite. The organic petrography analysis used the ICCP (International Committee for Coal and Organic Petrology, 1998, and 2001) and Pickel *et al*. (2017) for vitrinite, inertinite, and liptinite classification. Vitrinite reflectance is the proportion of incident light reflected from a polished vitrinite surface, which was measured by Random Vitrinite Reflectance Measurements (R_v% Random), using a random orientation of vitrinite nonpolarized white light. Vitrinite reflectance is commonly used to corroborate rank determinations based on calorific value, volatile matter, and fixed carbon contents. Vitrinite reflectance (R_v%) and maceral composition analyses used ASTM D2798-20 (2020) and ASTM D2799-13 (2013) as the standards.

CO_2 Adsorption Isotherm

Adsorption isotherm analysis was used to determine the maximum holding capacity of coal.

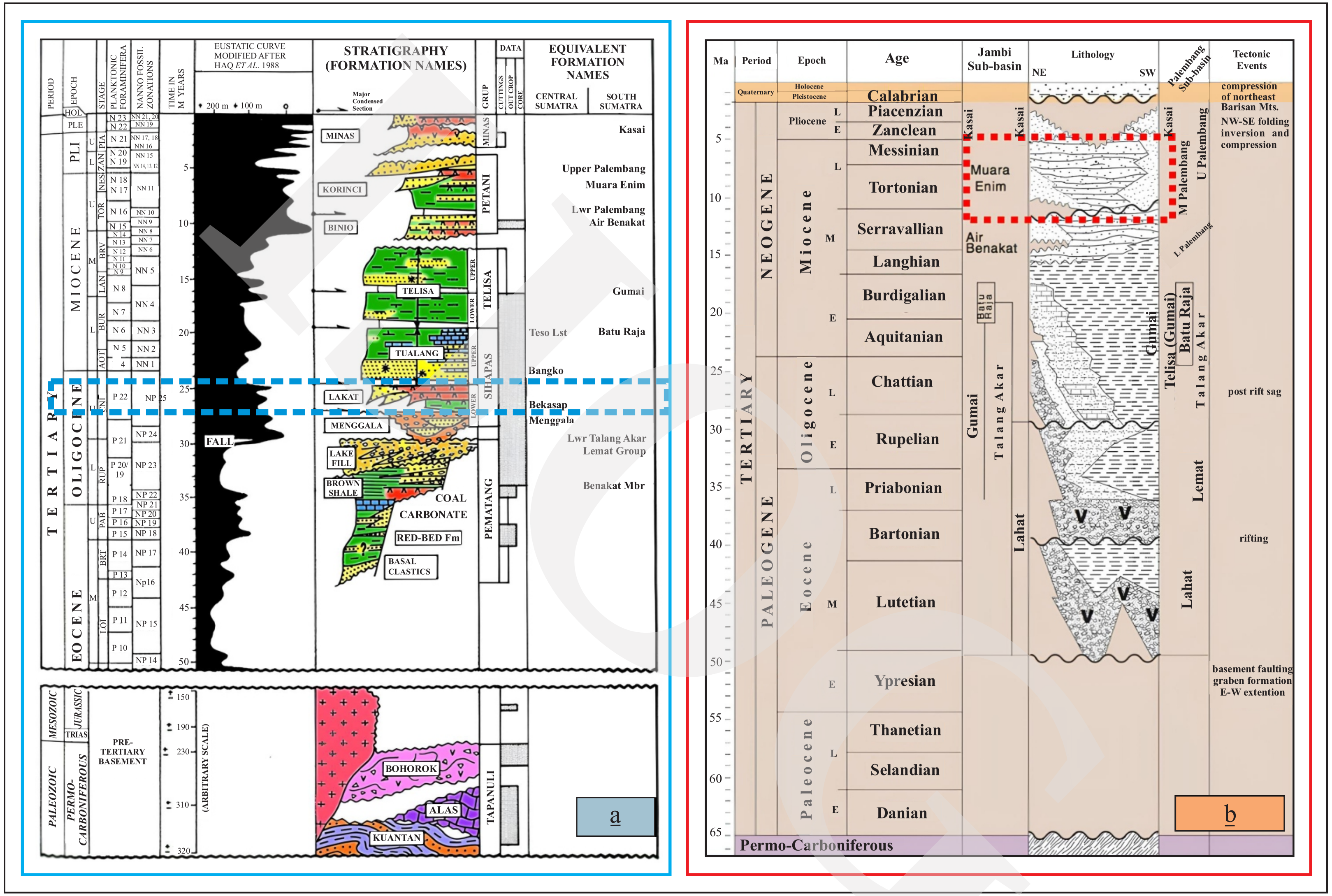

Figure 2. Stratigraphy of: a). Central Sumatra Basin with Lakat Formation as the study interest (blue box) (modified from Eubank and Makki, 1981) and b). Stratigraphy of South Sumatra Basin with Muaraenim as the study interest (red box) (Modified from Bishop, 2001) (B).

There is no specific standard for CO_2 adsorption isotherm analysis. Samples were received as lump coal, then crushed to approximately 4 mm in size. From this, approximately 150 g was subsampled, crushed to less than 0.212 mm, and brought to an equilibrium moist state. Isotherm determination was used to pressure steps up to a maximum pressure of around 6.78 MPa (999 psi). The analysis was performed at the formation temperature as close as possible. The temperatures were 46°C for Lakat coal samples and 33°C for Muaraenim coal samples. Isotherm results were tabulated and presented graphically as shown in Table 1 and Figure 3. Absolute isotherms results were calculated using standardized conditions of 20°C and 1 atmosphere (101.3 kPa) pressure per gram of coal.

RESULT AND DISCUSSION

The relationship between proximate, vitrinite reflectance, and maceral composition on CO_2 Adsorption Capacity was analyzed using simple linear regression. The moisture, ash, and fixed

Table 1. CO_2 Adsorption Capacity Data

COAL SAMPLES	PRESSURE (Mpa)	TEMPERATURE (°C)	ADSORBED CO_2 CONTENT (CC/G)		LANGMUIR EQUATION		FORMATION/ LOCATION
			ar	daf	ar	daf	
SU-01	0.28 - 6.78	46	2.1 - 18.78	3.45 - 31	$V_L = 31,42\ P / (P + 4,55)$	$V_L = 51,85\ P / (P + 4,55)$	Sungai Akar/ Lakat Formation
SU-03			2.3 - 21	3.16 - 28.63	$V_L = 35,74\ P / (P + 4,69)$	$V_L = 48,76\ P / (P + 4,69)$	
SP-10			2.6 - 25.98	3.25 - 31.56	$V_L = 43,77\ P / (P + 4,95)$	$V_L = 53,18\ P / (P + 4,95)$	
APU-03	0.28 - 6.78	33	1.71 - 23.96	2.59 - 37.62	$V_L = 45,97\ P / (P + 6,82)$	$V_L = 72,17\ P / (P + 6,82)$	Musi Banyuasin/ Muaraenim Formation
BRN-01			1.64 - 22.04	2.6 - 34.87	$V_L = 41,65\ P / (P + 6,55)$	$V_L = 65,90\ P / (P + 6,55)$	
SAK-01			1.72 - 23.14	2.72 - 36.43	$V_L = 43,08\ P / (P + 6,19)$	$V_L = 67,84\ P / (P + 6,19)$	
ASD-02			2.15 - 25.57	2.93 - 34.79	$V_L = 40,69\ P / (P + 4,45)$	$V_L = 55,35\ P / (P + 4,45)$	

Notes: ar = as receivd; daf = dry ash free V_L= Langmuir Volume; P = Langmuir Pressure.

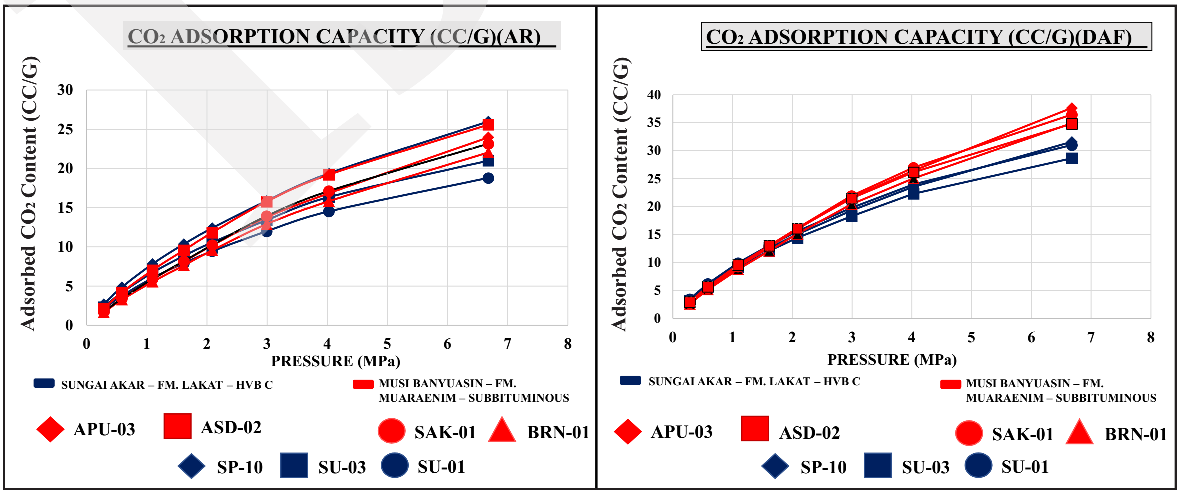

Figure 3. CO_2 Adsorption Capacity of Sungai Akar (blue) and Muaraenim coals (red) on as-received basis (left) and dry ash-free basis (right).

carbon contents were reported in as as-received basis since the adsorbed CO_2 content was also reported in the same basis. The adsorbed CO_2 content values to be plotted were the gas content at pressures of 4 MPa and 6.78 MPa. Assuming normal reservoir conditions, the pressure gradient would be constant at 0.98 MPa/100 m. The depth of the water table at the study site is 30 m (Rahmat *et al*., 2023). Therefore, the pressures of 4 to 6.78 MPa could be presumed to be equivalent to the pressures at depths of 450 to 700 m. As shown in Table 2, the proximate analysis indicates significant differences in moisture and ash content between the Lakat and Muaraenim coal samples.

Proximate, Ultimate, and Calorific Value Analyses

Significant variations in moisture and ash contents exist between the Lakat and Muaraenim coal samples. The Lakat coal has a total moisture content ranging from 13.48 to 19.66 % (ar). On the other hand, the Muaraenim coal has a higher moisture content, up to 2.5 times higher than Lakat coal, varying between 35.4 to 51.63 % (ar) (Table 2). In terms of ash content, the Lakat coal ranges between 4.2 and 20.7 % on an as-received (ar) basis, while the Muaraenim coal has five times smaller, varying between 0.8 and 2.9 % on as-received (ar) basis.

However, fixed carbon content of the Lakat coal is higher, ranging from 33.7 to 43.2 % (ar), compared to Muaraenim coal which varies from 18.9 to 30.6 % (ar). The calorific value does not show significant differences. Lakat coal has a calorific value from 5,246 to 6,885 cal/g (adb) or equivalent to 11,339 and 12,409 btu/lb on moisture, mineral matter-free basis. In comparison, Muaraenim coal has a slightly smaller range of 5,416 to 6,326 cal/g (adb) or equivalent to 7,797 and 8,841 btu/lb (moist, mmf). Based on ASTM rank classification, the calorific value of Muaraenim coal is categorized as lignite to subbituminous C (low rank) and Lakat coal is classified as subbituminous A to high volatile bituminous C (medium rank).

The comparison of the ultimate analysis of Lakat and Muaraenim coals reveals several key differences. Lakat coal has a higher total carbon content, ranging from 76.2 to 79.76 % (daf), whereas Muaraenim coal varies from 71.23 to 76.08 % (daf). Conversely, Lakat coal has a lower total oxygen content than Muaraenim coal, ranging between 10.86 and 15.72 % (daf) (Table 2).

Organic Petrographic Analysis

The vitrinite reflectance values of both the Lakat and Muaraenim coals indicate differences in their maturity levels and ranks. The Lakat coal

Table 2. Proximate, Ultimate, Calorific Value, and Maceral Composition Data

COAL SAMPLES	PROXIMATE					ULTIMATE		CV cal/g	MACERAL COMPOSITION				Formation/ Location
	MOISTURE (%)	ASH (%)		FC (%)		C (%)	O (%)		Rv	V (%)	I (%)	L (%)	
	ar	ar	adb	ar	adb	daf	daf	adb					
SU-01	16.71	20.7	25.74	33.7	38.9	76.2	15.72	5,246	0.55	86.2	5.6	1.8	**Sungai Akar/ Lakat Formation**
SU-03	13.48	13	15.08	35.3	39.43	79.76	10.86	6,403	0.57	76.8	6.2	11.4	
SP-10	19.66	4.2	5.27	43.2	51.73	78.68	13.55	6,885	0.54	80.6	6	1.6	
APU-03	51,53	2	3,51	22.4	39,86	71.23	21.32	5,246	0.33	69	22.8	2.2	**Musi Banyuasin/ Muaraenim Formation**
BRN-01	48,15	2.9	4,97	22.5	38,18	72.05	19.9	6,403	0.4	73.2	19	5	
SAK-01	50,45	1.5	2,69	18.9	34,71	72.99	19.65	6,295	0.35	67.6	22.6	4.8	
ASD-02	35,4	0.8	1,09	30.6	40,93	76.08	16.31	6,885	0.41	68.4	19.2	10.4	

FC: Fixed Carbon; C: Carbon; O: Oxygen; CV: Calorific Value; Rv: Vitrinite Reflectance; V: Vitrinite; I: Inertinite; L: Liptinite; CO_2: Carbon Dioxide; adb: Air-Dried Basis ranges from 0.54 to 0.57 %, while the Muaraenim coal has a smaller range of 0.33 to 0.41 %. The vitrinite content varies from 76.8 to 86.2 % in the Lakat coal and 67.6 to 73.2 % in the Muaraenim one. Inertinite content is from 5.6 to 6.2 % in the Lakat coal and 19 to 22.8 % in the Muaraenim coal (Table 2). The Lakat coal has the higher vitrinite content than Muaraenim coal, while Muaraenim coal has the higher inertinite content. The liptinite group is the least abundant maceral group in both coals with a content range of 1.6 to 11.4 % in the Lakat coal and 2.2 to 10.4 % in the Muaraenim one.

CO_2 Adsorption Capacity Analysis

The carbon dioxide content from adsorption isotherm analysis is presented on as-received basis (ar) and dry ash-free basis (daf). As-received basis was used to calculate the carbon dioxide amount that could be stored in coal resources, and to analyze the relationship between coalbed reservoir properties and gas content (adsorbed CO_2 content). In contrast, the dry ash-free basis was employed to analyze the coal rank and its organic composition effect on gas content in coal (Moore, 2012). The adsorbed CO_2 content on an as-received basis is smaller than the dry ash-free basis. Isotherm results were tabulated and presented graphically as shown in Figure 3.

The adsorption analysis (Figure 3) indicates that adsorbed CO_2 content increases with pressure up to 7 MPa. For instance, at 7 MPa, Lakat coal adsorbed CO_2 content varies from 18 to 26 cc/g, while Muaraenim coal shows the range from 0.5 to 3.5 cc/g (Table 1). Characteristics of the Langmuir Isotherm curve on as-received basis and dry ash-free basis exhibit different pattern (Figure 3). On the as-received basis, the difference in adsorbed CO_2 content values starts to be visible at the pressure of 1 MPa. On the pressure of 1 - 2 MPa, the adsorbed CO_2 content in the Lakat coal ranges between 5 and 13 cc/g with a difference of about 12−cc/g for each sample. Then at the pressure of 7 MPa, the difference in the adsorbed CO_2 content is very significant, reaching about 5 cc/g with the lowest adsorbed CO_2 content of 18 cc/g in the sample SU-01 and the highest 26 cc/g in the SP-10 sample (Figure 3). The differences in adsorbed CO_2 content between these two bases is also quite significant. At low pressure (0.28 - 1 MPa), an increase ranges from 0.6 to 1.5 cc/g. Whilst at a high pressure (7 MPa), the increase is much greater, varying from 5 to 14 cc/g.

The Langmuir Isotherm curve of Muaraenim coal is distinguishable from that of Lakat coal. The differences in adsorbed CO_2 content of the Muaraenim coal, both on an as-received basis and a dry ash-free basis are various. On an as-received basis, the adsorbed CO_2 content ranges from 0.3 to 1.5 cc/g at low pressure (1 - 2 MPa) and 0.5 to 3.5 cc/g at high pressure (7 MPa) (Figure 3). On the dry ash-free basis, the differences in adsorbed CO_2 content between the two samples become more evident at pressures of 4 - 7 MPa. The increase in carbon dioxide gas content from the as-received base to the dry ash-free base varies between 0.8 to 1 cc/g at the pressure of 0.28 MPa and 9 to 13 cc/g at a pressure of 7 MPa. The discrepancy in adsorbed CO_2 content values between the two bases can be attributed to the removal of moisture and ash in the dry ash-free basis.

Effect of Coal Rank on CO_2 Adsorption Capacity

The rank of coal affects its ability to adsorb CO_2. According to the CO_2 adsorption capacity analysis in dry ash-free basis, the gradient of adsorbed CO_2 content curve differs between pressures of 4 MPa and 6.78 MPa. Lakat coal, classified as subbituminous A - high volatile bituminous C rank, has a lower adsorbed CO_2 content compared to Muaraenim coal classified as lignite-subbituminous C (Figure 3). Vitrinite reflectance value also has a strong impact on adsorbed CO_2 content. The cross-plot between vitrinite value and adsorbed CO_2 content indicates a strong negative relationship, with a correlation coefficient of 0.88 at 4 MPa and 0.96 at 6.78 MPa (Figures 4a and 4c). Higher coal rank led to lower adsorbed CO_2 content. This finding aligns with previous studies indicating gas adsorption capacity decreases until the bituminous rank before

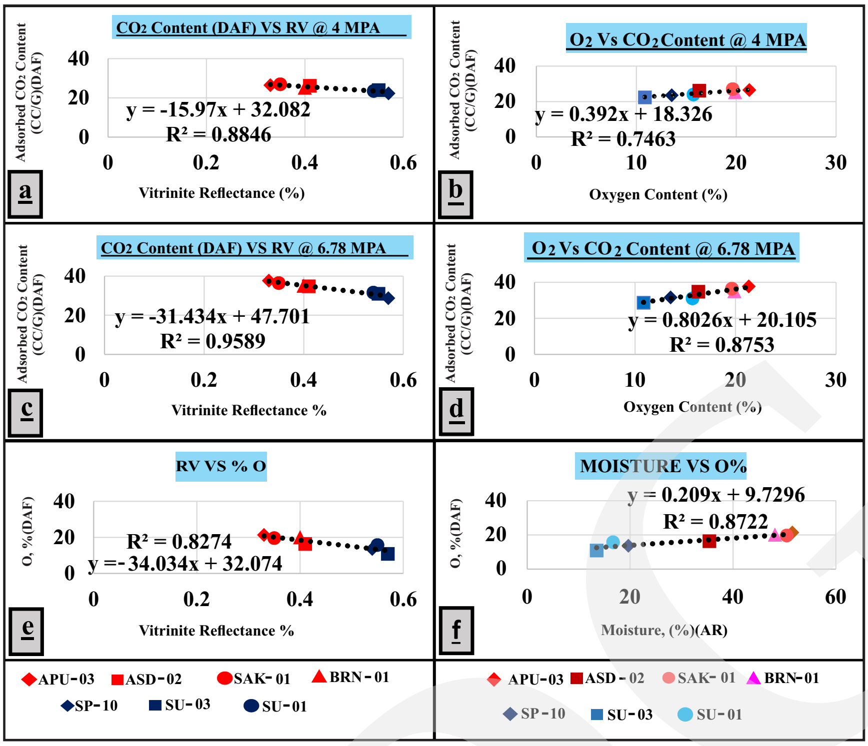

Figure 4. Crossplot between: (a and c) vitrinite reflectance vs adsorbed CO_2 content, (b and d) O_2 content and adsorbed CO_2 content, (f) moisture and O_2 content, and (e) vitrinite reflectance and O_2.

increasing again (Laxminarayana and Crosdale, 1999; Busch and Gensterblum, 2011; Zhang *et al*., 2011; Gensterblum *et al.,* 2013; Merkel *et al.,* 2015).

Changes in coal rank led to changes in the composition of coal, both in terms of its chemical and maceral composition. Higher rank will decrease the capacity of coal to adsorb carbon CO_2. Coal contains macropores and micropores, as well as a surface area that can adsorb CO_2. When the rank of coal increases from subbituminous to high volatile bituminous, the total volume of pores (both macropores and micropores) decreases, resulting in lower adsorbed CO_2 content in the coal (Flores, 2014). As coal undergoes compression and burial, the decrease in porosity is offset by the formation of kerogen and secondary porosity, which alters the size of larger pores into micropores during coal maturation (Prinz and Littke, 2005)

Besides the changes in micropore volume, changes in the surface chemical structure of coal can affect the CO_2 adsorption capacity in coal. As coal matures, the surface chemistry changes, leading to the loss of functional groups and the breaking of aromatic bonds. This condition impacts the adsorption capacity of CO_2. The difference in oxygen-containing functional groups also influences the adsorption capacity, which can be measured through the total oxygen content based on ultimate analysis. The Muaraenim coal has a higher total oxygen content compared to the Lakat coal, and this higher oxygen content is correlated with the presence of oxygen-containing functional groups that are responsible for gas adsorption (Day *et al*., 2008). As the result, Muaraenim coal classified as subbituminous rank coal, which has more oxygen-containing functional groups, tends to have a higher adsorbed CO_2 content due to its higher adsorption capacity (Figures 4b and 4d).

Effect of Moisture on CO_2 Adsorption Capacity

The moisture content and adsorbed CO_2 content in Lakat coal exhibit a weak positive correlation (correlation coefficient= 0.35 at 4 MPa and 0.43 at 6.78 MPa) (Figures 5a and 6a). This weak positive

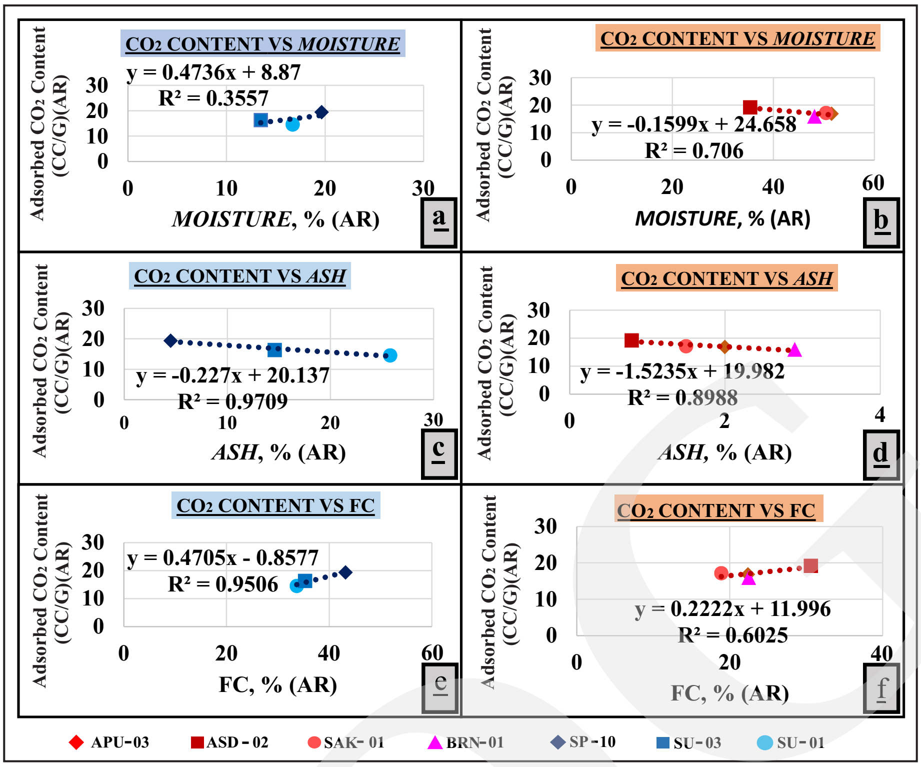

Figure 5. Cross-plot between chemical composition vs adsorbed CO_2 content in Lakat (blue) and Muaraenim (red) coal at 4 MPa: (a and b) moisture content and adsorbed CO_2 content, (c and d) ash and adsorbed CO_2 content, (e and f) fixed carbon (FC) and adsorbed CO_2 content.

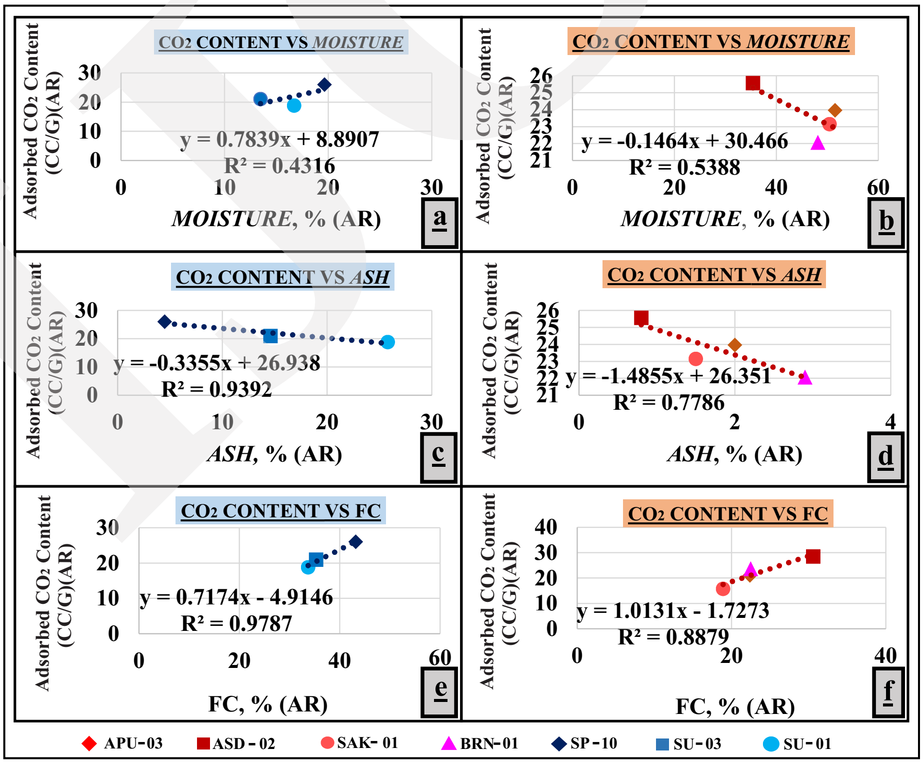

Figure 6. Cross-plot between chemical composition vs adsorbed CO_2 content in Lakat (blue) and Muaraenim (red) coal at 6.78 MPa: (a and b) moisture content and adsorbed CO_2 content, (c and d) ash and adsorbed CO_2 content, (e and f) fixed carbon (FC) and adsorbed CO_2 content.

correlation is different from previous studies that typically showed a negative correlation (Ozdemir and Schroeder, 2009; Švábová *et al*., 2012; Gensterblum *et al*., 2013; Wang *et al*., 2020). Similar positive correlations between moisture and gas content have also been found in North China on medium to high-ranked coals (Zhao *et al*., 2019). Moisture are usually in the micropore of coal which is affected by its maceral composition. This positive relationship might be related with its maceral composition (Teng *et al*., 2017). It is also worth noting that the range of moisture content values in the Lakat coal only differs slightly by 3 %, which is a significantly different from other studies where the difference in moisture content between samples on the same rank is much greater.

In contrast to the Lakat coal, the moisture content in Muaraenim coal has a negative relationship with adsorbed CO_2 content (Figures 5b and 6b). The correlation coefficient value obtained is 0.7 at a pressure of 4 MPa and 0.53 at a pressure of 6.78 MPa. This coefficient value indicates that the relationship between the value of water content and carbon dioxide gas content in the Muaraenim coal is fairly good. Adsorbed CO_2 content decreased by 1 - 2 cc/g at pressures of 4 MPa and 6.78 MPa with an increase in the water content of 13 % (ar).

The effect of moisture content is more significant in low-ranked (subbituminous) coals compared to higher-ranked (high-volatile bituminous) as presented by higher coefficient correlation in Muaraenim coal (Figures 5b and 6b). CO_2 adsorption capacity increases with increasing oxygen content. Oxygen content can be correlated with the number of oxygen-containing groups (Gensterblum *et al*., 2013). An increase in these oxygen-containing groups will generally increase the adsorbed CO_2 content (Figures 4b and 4d), and reduce the pressure in the coal pores (Tenney and Lastoskie, 2006).

A higher moisture content leads to a smaller capacity for adsorbing CO_2, because water molecules tend to fill the spaces in coal, reducing the available space for methane or carbon dioxide gas molecules (Švábová *et al*., 2012; Merkel *et al*., 2015). Additionally, Romanov *et al*. (2013) stated that moisture in the coal matrix could clog micropores interfering with gas adsorption. Several mechanisms contribute to the decrease in CO_2 gas adsorption capacity, including the formation of clusters in open pores that close off pore space, competition for adsorption sites (Day *et al*., 2008), reduced gas diffusion (Pan *et al*., 2010), and induced swelling (Krooss *et al*., 2002). Low-rank coal, which has high porosity and polar groups like hydroxyl and carboxyl, can adsorb more water compared to higher-rank coals (Crosdale *et al*., 1998; Gensterblum *et al*., 2013) as presented by higher moisture content in the Muaraenim coal compared to the Lakat one (Table 2). Overall, the presence of moisture in coal negatively affects its ability to adsorb CO_2.

Effect of Ash Content on CO_2 Adsorption Capacity

According to the cross-plot analysis, a negative correlation between the ash content and adsorbed CO_2 content in Lakat and Muaraenim coals was identified. The correlation values of 0.97 and 0.93 for Lakat coal, and 0.89 and 0.78 for Muaraenim coal, respectively indicate a very strong negative relationship between the two parameters at both locations (Figures 5c, 5d, 6c, and 6d). In Lakat coal, the higher ash content leads to a smaller adsorbed CO_2 content in the coal. Specifically, an increase in ash content by 10 % (ar) resulted in a decrease in adsorbed CO_2 content by 1 - 3 cc/g. Similarly, in Muaraenim coal, an increase in ash content by 0.5 - 1.4 % (ar) leads to a decrease in adsorbed CO_2 content by 1 - 2 cc/g (Figure 5d and 6d). These findings highlight the negative impact of ash content on adsorbed CO_2 content.

This study was supported by previous research findings that ash had a negative impact on the gas adsorption capacity and carbon dioxide content (Laxminarayana and Crosdale, 1999, 2002; Faiz *et al*., 2007; Weniger *et al*., 2010; Mohanty *et al*., 2018; Kumar *et al*., 2019). The presence of mineral matters in coal pores leads to a decrease in carbon dioxide gas adsorption capacity. Additionally, high ash content reduces the surface area of coal, which is negatively correlated with ash content (Morse *et al*., 2010). The content and type of minerals present in coal are closely related to ash content. According to Laxminarayana and Crosdale (1999), mineral materials act as fillers or diluents in coal, resulting in a decrease in its gas adsorption ability.

Effect of Fixed Carbon Content on CO_2 Sorption Capacity

The fixed carbon content of Sungai Akar and Muaraenim coals has a positive impact on the adsorbed CO_2 content at pressures of 4 MPa and 6.78 MPa. The correlation coefficient values obtained indicate a strong relationship between the fixed carbon content and adsorbed CO_2 content, with values of 0.95 at 4 MPa and 0.97 at 6.78 MPa (Figures 5e, 5f, 6e, and 6f). Increasing the fixed carbon content by 3 - 4 % results in an increase of 2 - 4 cc/g of adsorbed CO_2 content at 4 MPa, and an increase of 2 - 5 cc/g at 6.78 MPa. The correlation coefficient values obtained for Muaraenim coal are 0.6 at 4 MPa and 0.88 at 6.78 MPa. The total carbon content in the ultimate analysis is also directly proportional to the fixed carbon content in Lakat and Muaraenim coals.

This finding aligns with previous studies, *e.g.* Dutta *et al*. (2011), Mohanty *et al*. (2018), Kumar *et al*. (2019). Dutta *et al*. (2011) found that there was an increase of 40 ml/g with 0.15 % increase in fixed carbon content. Similarly, Levy *et al*. (1997) observed that methane gas adsorption capacity increased by 3 ml/g with a 10 % increase in fixed carbon content. This can be attributed to the fact that the presence of fixed carbon leads to the formation of micro and mesopores, which provide spaces for gas adsorption within the coal matrix, as highlighted by Kumar *et al.* (2019).

Effect of Maceral Compositions on CO_2 Sorption Capacity

Lakat coal has a different maceral composition from Muaraenim coal. Analysis of the effect of maceral composition on carbon dioxide gas content is only conducted on vitrinite and inertinite content. This is because these two groups of macerals have a significant content, thus it is considered to affect the adsorbed CO_2 content. The adsorption capacity analysis was carried out on a dry ash-free (daf) basis.

Effect of Vitrinite Content on CO_2 Sorption Capacity

The vitrinite content of Lakat coal ranges between 76.8 and 86.2 %. The cross-plot between the value of vitrinite content vs adsorbed CO_2 content, depicts a positive relationship (Figure 7a). Adsorbed CO_2 content increased by 0.5 to 1.5 cc/g with an increase in vitrinite content of 4 - 6 %. The correlation coefficient obtained was 0.85 at a pressure of 4 MPa and 0.46 at a pressure of 6.78 MPa. The relationship between the two parameters is very good at a pressure of 4 MPa compared to a pressure of 6.78 MPa. This difference is due to the shifting in the difference of adsorbed CO_2 content and position in the SP-10 and SU-01 samples in the pressure range from 4 MPa to 6.78 MPa.

Contrary to Lakat coal, the vitrinite content of Muaraenim coal has a negative correlation with CO_2 content (Figure 7b). Adsorbed CO_2 content decreased by 1.5 to 2 cc/g with an increase in vitrinite content by 0.6 - 4 %. The correlation coefficient obtained was 0.9 at a pressure of 4 MPa and 0.19 at a pressure of 6.78 MPa. The relationship between the two parameters is very good correlation at a pressure of 4 MPa compared to a pressure of 6.78 MPa which shows a very poor correlation. This difference is due to the change in the value of adsorbed CO_2 content and position in all samples in the pressure range of 4 MPa to 6.78 MPa. In the pressure interval of 1.7 MPa to 4 MPa, the position of all curves is always the same with the relatively small difference in carbon dioxide gas content value compared to the pressure in the range of 4 MPa to 6.78 MPa.

The relationship between vitrinite content and adsorbed CO_2 content in Lakat coal confirms previous studies that show vitrinite-containing coal has more pores and therefore has higher adsorbed CO_2 content compared to coal containing inertinite (Crosdale *et al*., 1998; Mastalerz *et al*., 2004; Chalmers and Marc Bustin, 2007). A

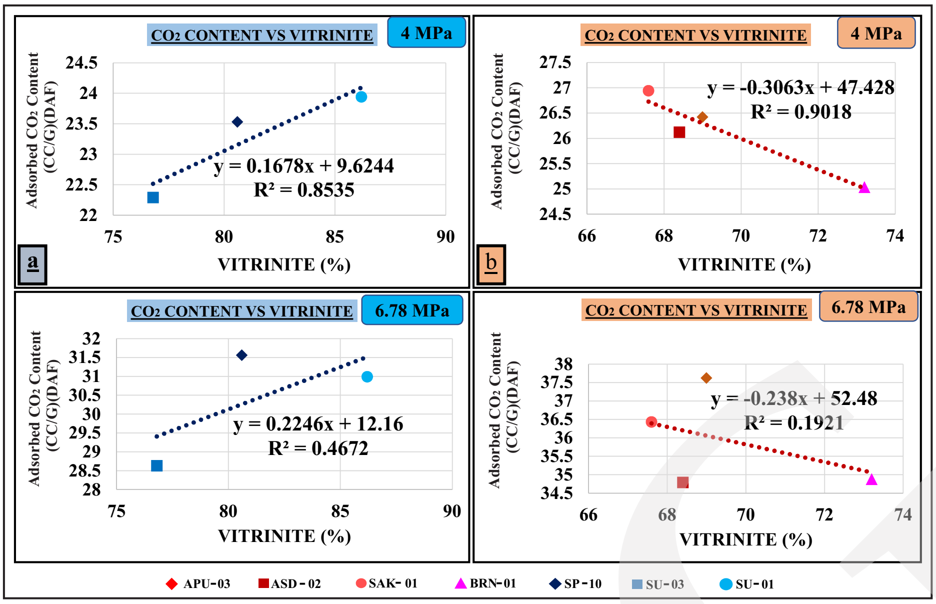

Figure 7. Cross-plot between Vitrinite Content vs Adsorbed CO_2 content in: (a) Lakat Coal (blue) and (b) Musi Banyuasin (red).

research in the upper Silesian Basin found that high volatile bituminous coal with higher vitrinite content also had higher micropore content (Weishauptová *et al.*, 2015). Similarly, in Chinese high and low-volatile bituminous coal, vitrinite content was found to increase the adsorption capacity of methane gas (Liu *et al.*, 2015). The addition or increase of inertinite content weakens this relationship (Mastalerz *et al.*, 2004). Vitrinite has the ability to produce more gas in pores and micropores compared to inertinite, leading to a greater pore volume and surface area in medium and high-ranked coals.

In contrast to Lakat coal, vitrinite content in Muaraenim coal has a negative relationship with CO_2 adsorption capacity. In low rank coal, micropore and mesopore content is strongly influenced by inertinite content (Liu *et al.*, 2015).

Effect of Inertinite Content on CO_2 Sorption Capacity

The Lakat coal has an inertinite content ranging from 5.6 % to 6.2 %. There is a negative correlation between the inertinite content and adsorbed CO_2 content in this coal (Figure 8a). An increase in the inertinite content by 0.2 - 0.4 % leads to a decrease in adsorbed CO_2 content by 0.5 to 1.5 cc/g. The correlation coefficient is 0.79 at a pressure of 4 MPa and 0.38 at a pressure of 6.78 MPa, indicating a strong correlation at a pressure of 4 MPa compared to a poor correlation at 6.78 MPa (Figure 8a). This difference is attributed to variations in the adsorbed CO_2 content in the specific pressure range.

On the other hand, the Muaraenim coal has an inertinite content varying from 19 % to 22.8 %. In this coal, there is a positive relationship between the inertinite content vs adsorbed CO_2 content (Figure 8b). An increase in the inertinite content by 3.4 % leads to an increase in adsorbed CO_2 content by 1.5 to 2 cc/g. The correlation coefficient is 0.64 at a pressure of 4 MPa and 0.89 at a pressure of 6.78 MPa, indicating a strong correlation at both pressures.

In high volatile bituminous coal, the gas adsorption capacity is mostly controlled by micropores. The micropore content of these coals is highly influenced by the vitrinite content. Inertinite content has a negative correlation with micropore volume in similarly ranked coals in the Pennsylvania Basin (Mastalerz *et al.*, 2008). Inertinite content has a positive correlation to mesopore volume. Inertinite content also shows a negative correlation in higher rank coals (Dutta *et al.*, 2011).

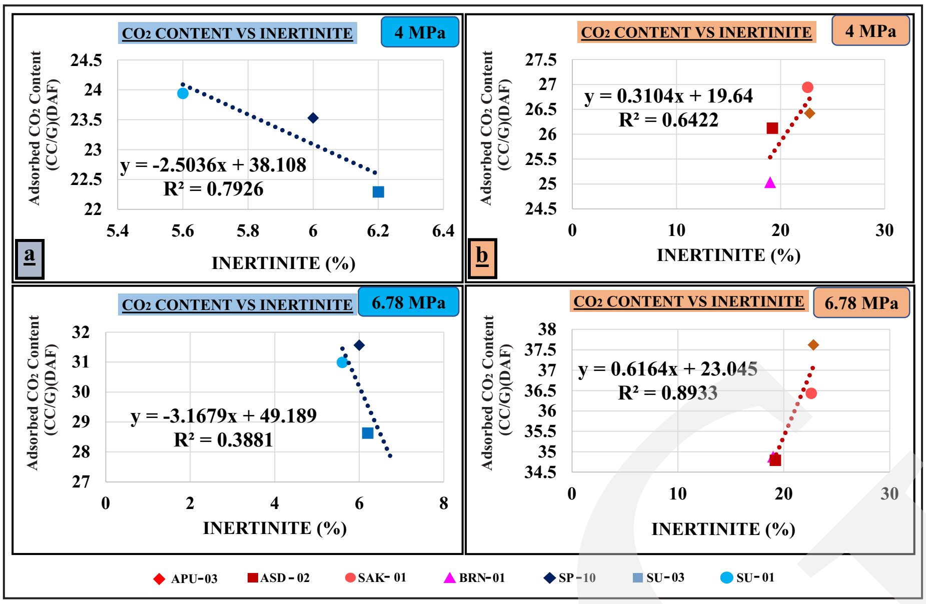

Figure 8. Cross-plot between inertinite content vs adsorbed CO_2 content in Lakat coal (blue, a) and Musi Banyuasin (red, b).

In low rank coals (lignite - subbituminous) inertinite content has more influence on the gas adsorption capacity. This is because the micropore content in low-rank coal is much more in inertinite and has the characteristics of open pores and semi-open pores (Liu *et al*., 2015). Jian *et al.* (2015) revealed that increasing inertinite content in low-rank coal would increase the volume and surface area of mesopores and macropores in coal. The volume of micropores in coal will increase until the inertinite content reaches 20 % and then will decrease until the inertinite content was 60 % and increase again.

Conclusion

Lakat coal has differences in chemical and organic composition from Muaraenim coal. Based on ASTM Coal Rank classification and its vitrinite reflectance value, the Lakat coal categorized as medium rank (subbituminous A-high volatile C bituminous) has lower CO_2 adsorption capacity than the Muaraenim coal (lignite-subbituminous C). The differences in rank, chemical, and organic composition between Lakat and Muaraenim coals significantly impact their CO_2 adsorption capacities.

In terms of the chemical composition, it was observed that ash and moisture content will reduce the CO_2 adsorption capacity in coal. However, there was a very weak positive correlation between the moisture content and CO_2 adsorption capacity in the Lakat coal. On the other hand, fixed carbon content had a positive correlation with CO_2 adsorption capacity in both coals.

Regarding maceral composition, vitrinite and inertinite content had an inverse correlation with CO_2 adsorption capacity in both coals. The Lakat coal exhibited a higher vitrinite content compared to the Muaraenim coal, while the Muaraenim coal had a greater inertinite content than the Lakat coal. The vitrinite content showed a positive relationship with CO_2 adsorption capacity in the Lakat coal and a negative relationship in the Muaraenim coal. Inertinite content, on the other hand, had a positive correlation in the Muaraenim coal and a negative correlation in the Lakat coal.

These findings suggest that low-rank coals like Muaraenim may be more suitable for CCS applications based on its CO_2 adsorption capacity. Future research should focus on the long-term CO_2 sequestration stability and the economic feasibility of using these coal types for CCS.

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