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Characterisation of Minerals and Other Properties of Mukah Coal

Shaktivell Letchumanan[1], Nur Azam Badarulzaman[1]*, Hazman Seli[2], Amkpa Job Ajala[3]

[1]Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Johor, MALAYSIA

[2]Faculty of Chemical Engineering,
Universiti Teknologi MARA (UiTM), 94300 Kota Samarahan, Sarawak, MALAYSIA

[3]Federal Polytechnic Idah,
PMB 1037, Idah, Kogi State, NIGERIA

*Corresponding Author

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Abstract: An increase in human population correlates with an increase in demand for energy. Coal has been a vital energy source for human populations for millennia, where it has played a major role in various industries, especially in the thermal-based industries. Coal is found in all three geographical provinces of Malaysia: Peninsular Malaysia, Sarawak, and Sabah. However, at most, the widespread and abundant occurrences of coal are found in Sarawak, especially in Mukah. The age of the coal deposits found in Mukah has instigated research that focuses mainly on the characterization of minerals and other properties in the coal, where those findings could be used to propose coal usage in other types of industries. To achieve those objectives, this research starts with a theoretical approach by discussing the coalification process, followed by understanding the types of coal produced from this process. Basic coal analysis, visual inspection, proximate analysis, XRD, SEM-EDX, and FTIR analysis were done to achieve all the objectives. At the end of the research, it was found that the Mukah coal sample is denser and has a higher gold content compared to the commercial coal sample. It was seen that the commercial coal possessed a high caloric value compared to the Mukah coal. This may be due to the high moisture and silicone content in the coal sample as it is mined directly from the earth. Overall, the Mukah coal sample could be used for other industries, like the fertilizer industry, rather than just being used to generate electricity by burning.

Keywords: Energy source, abundant, characterisation of minerals, coalification process, proximate analysis

1. Introduction

Coal is geographically spread across all inhabitable continents of the world. In general, a coal's physical appearance is known as a black or brownish-black organic sedimentary rock of biochemical origin that is combustible. Basically, coal is composed primarily of carbon with chemical proportions of hydrogen, nitrogen, oxygen, and sulfur. Coal has been a vital energy source for human populations for millennia. It is a result of vegetable accumulation debris in a specialized environment of depositions. Coal has played a major role in various industries, especially in the thermal based industries. Coal is the primary fuel source for generating power [1].

*Corresponding author: azam@uthm.edu.my

Peninsular Malaysia, Sarawak, and Sabah are Malaysia's three geographical provinces, and all three have coal deposits. However, at most, the widespread and abundant occurrences of coal are found in Sarawak. Through the systematic geological mapping carried out by the Geological Survey in the past decades, various deposits that are known to be of economic importance have been outlined, and the major deposits are in the Silantek, Merit-Pila, Mukah-Balingian, and Bintulu areas [2]. Since Sarawak has installed a coal-power plant in Mukah [3], the importance of Mukah's coal is undeniable. This research focuses on evaluating the mineralogy and chemical composition of Mukah coal. Furthermore, this research aims to evaluate the physical and thermal properties of coal and eventually propose its applications to other industries.

Coal consists of both organic and inorganic material, which is chemically and physically heterogeneous. Coal is the most reachable and economic fossil resource on the earth. Normally, coal is described as an organic sediment, whereby it is also known as combustible sedimentary rock or biolite. The major chemical elements in coal are carbon, hydrogen, and oxygen. Carbon is a chemical element that can exist in a certain allotropic form, including as diamond and graphite.

1.1 Origin of Coal

Coal is found in deposits called seams that are made from decayed, accumulated plant remains and other organic detritus that have undergone physical and chemical changes. These changes include the decaying of vegetation, deposition and burial by sedimentation, compaction, and transformation of the plant remains into the organic rock found today. The quality of coal around the world differs based on the type of plant material that has been deposited, the degree of metamorphism or coalification, and the range of included impurities [4]. The quality of the coal improves when it transforms from the biochemical phase to the geochemical phase [5]. Time, temperature, and heat play a major role in the coalification process, where these three elements can efficiently increase the final product of the coal, which is anthracite.

1.2 Coal Occurrence in Mukah, Sarawak

The Mukah coal is located in Sarawak's central coastline region. Twelve associated coal seams were found during explorations by Malaysia's Geological Survey Department. Among these coal seams, five are major and seven are minor seams [6]. This formation typically has coal seams that are less than 2 meters thick, but in actuality, it has coal that is 2.24 meters thick. The sub-bituminous B rank coal in this area is appropriate for use in coal-fired power plants. According to Fig. 1, there are 551.9 million tons of coal reserves that have been determined based on the five commercially viable and well-developed coal seams. Of these, 20.0 million tons are measured reserves, 80.8 million tones are indicated reserves, and 451.1 million tons are inferred reserves.

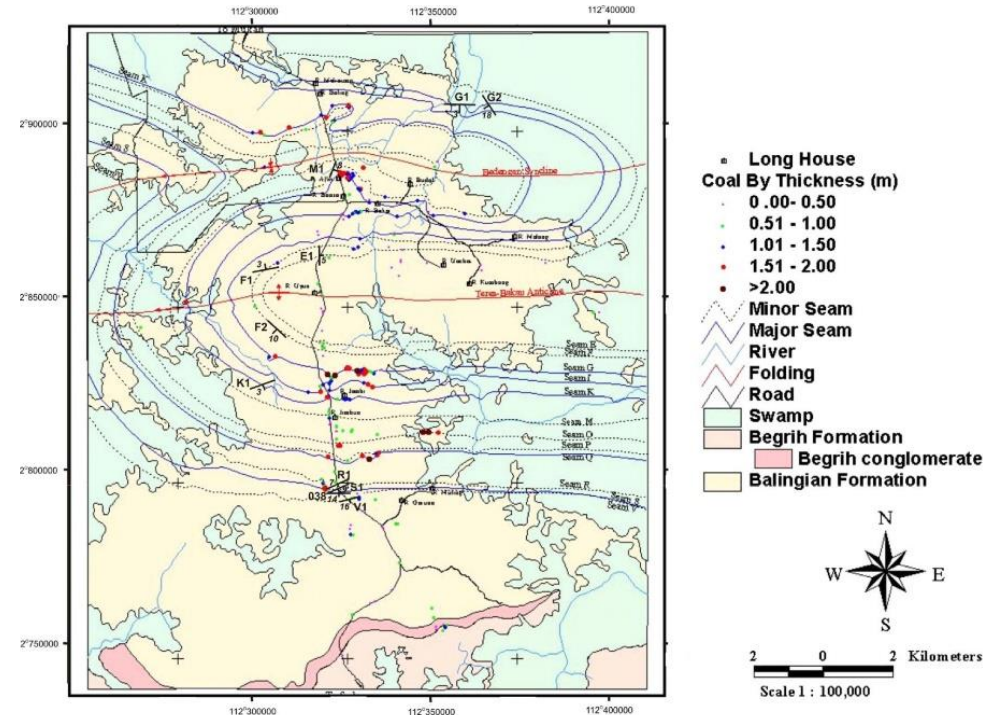


Fig. 1 - Geological map of the Mukah coalfield, the twelve correlated coal seams and the sampling points [6]

1.3 Classification of Coal

Therefore, there were two types of classification systems. The first one was to aid the scientific studies that are concerned with the origin, composition, and fundamental properties of coal [7]. The second was to assist the commercial system that includes coal producers and users, which focused on market issues such as technological properties and the utilization of coal based on suitability. Classification of coal is also needed to differentiate the characteristics of coal and the boiler furnace in use, to identify the applications of coal in chemical technology and metallurgy, and to extend the trade of coal [4]. Before discussing the classification system of coal by rank, grade, and type, we have to identify the basic analyses that should be done before progressing. The information that we obtained from this analysis will somehow give us a clear picture of what needs to be found or identified during the classification.

There are three main analyses that should be done to classify the coal. Two are related to chemical analyses, and one is related to caloric determination. In chemical analyses, proximate and ultimate analyses are done [7]. Proximate analysis covers the content of the moisture, ash, volatile matter, and caloric value, while ultimate analysis covers the content of several chemicals such as carbon, hydrogen, nitrogen, sulfur, and oxygen. The following Fig. 2 gives a major outline of the relationship between the coal components and the analyses that can be done. This outline is very important, as it will identify and justify the appropriate properties.

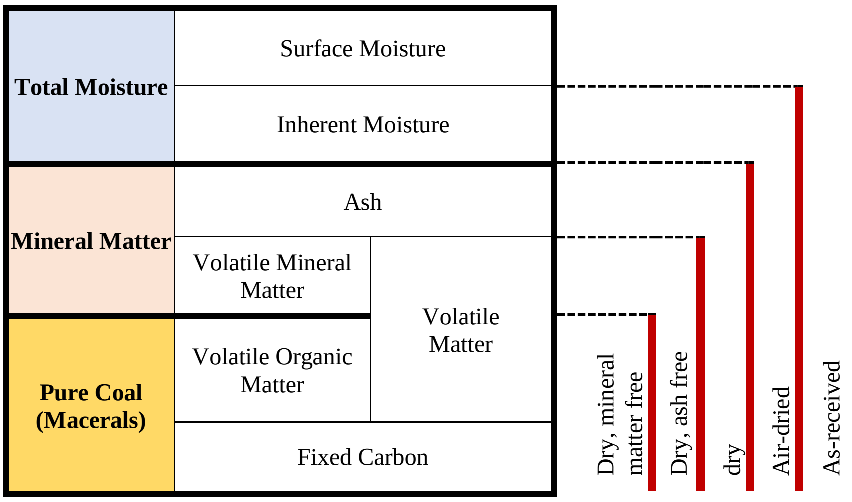


Fig. 2 - The relationship of different analytical bases to coal components [8]

The classification system is very much needed to maintain the quality of the coal. Generally, the American Society for Testing and Materials (ASTM) and the International Classification or Codification System are used in common based on desired properties. It is interesting to note that in all countries, the classification systems used commercially are primarily based on the content of volatile matter in the coal. The lower the volatile matter, the higher the quality of the coal. Table 1 is the coal classification according to rank by ASTM. This table justifies the quality of the coal and its use as well.

Table 1 - Coal classification according to rank by ASTM D388-19a [7]

Class And Group	Fixed Carbon (%)	Volatile Matter	Heating Value (Btu/Ib)
Anthracitic			
1. Meta-anthracite	> 98	< 2	-
2. Anthracite	92 - 98	2 - 8	-
3. Semi-anthracite	86 - 92	8 - 14	-
Bituminous			
1. Low-volatile bituminous coal	78 - 86	14 - 22	> 14,000
2. Medium-volatile bituminous	69 - 78	22 - 31	13,000 - 14,000
coal	< 69	> 31	10,500 - 13,000
3. High-volatile A bituminous	-	-	-
coal	-	-	-
4. High-volatile B bituminous coal			
5. High-volatile C bituminous coal			

Sub-bituminous			
1. Sub-bituminous A coal	-	-	10,500 - 11,500
2. Sub-bituminous B coal	-	-	9,500 - 10,500
3. Sub-bituminous C coal	-	-	8,300 - 9,500
Ligitic			
1. Lignite A	-	-	6,300 - 8,300
2. Lignite B	-	-	< 6,300

1.4 Major Components of Coal

This section discusses only the element that usually exists in coal. This could be a guide in analyzing the Mukah coal. The elemental content in commercial coal is as stated in Table 2.

Table 2 - The typical properties of coal [7].

Elements	Class	
Sulphur content in coal	○ Anthracite	: 0.6 - 0.77 % w/w
	○ Bitunimous coal	: 0.7 - 4.0 % w/w
	○ Lignite	: 0.4 % w/w
Moisture content in coal	○ Anthracite	: 2.8 - 16.3 % w/w
	○ Bitunimous coal	: 2.2 - 15.9 % w/w
	○ Lignite	: 39 % w/w
Fixed carbon in coal	○ Anthracite	: 80.5 - 85.7 % w/w
	○ Bitunimous coal	: 44.9 - 78.2 % w/w
	○ Lignite	: 31.4 % w/w
Bulk density of coal	○ Anthracite	: 800 - 929 kg/m^3
	○ Bitunimous coal	: 673 - 913 kg/m^3
	○ Lignite	: 641 - 865 kg/m^3
Mineral matter content (as mineral ash)	○ Anthracite	: 9.7 - 20.2 % w/w
	○ Bitunimous coal	: 3.3 - 11.7 % w/w
	○ Lignite	: 4.2 % w/w

2. Methodology

For this research, market-available or commercial coal should be considered as a point of comparison.. It is used to compare commercial coal with the coal from Mukah from the perspectives of physical properties, mineral content, chemical composition, and thermal properties. Table 3 gives a general idea of the scope that is useful in achieving the aim of the research. The scopes are categorized according to the properties. Some of the properties will be considered based on the objectives. Referring to the table, the scopes were classified based on three properties, and all three properties are related and important to this research.

Table 3 - The property analysis of coal [7]

Properties		**Comments**
Physical	**Density***	True density
	Porosity and surface area	Nature of pore structure
	Surface area	Surface characteristics
Mechanical	Strength	Ability to withstand external forces
	Hardness index	Measurement of scratch hardness
	Friability	Ability to withstand degradation during handling
	Grindability	Energy needed to pulverise or grind coal
	Dustiness index	Amount of dust produced during handling
Thermal	Heat capacity	Indication of energy content
	Thermal conductivity	Rate of heat transfer through unit area
	Plastic properties	Charges of coal on or during heating
	Agglutinating properties	Changes of on or during heating
	Free swelling index	Determination of nature of residue after heating
	Ash fusion temperature	• Increase in volume when coal is heated • Behaviour of ash during combustion

***** *analyses which was carried out in this work***

At first, the commercial coal sample and the Mukah coal sample are analyzed visually from the images obtained from both the microscopic view and the DSLR camera. The samples are then broken down into 63 µm sized particles using the sieving machine for further experimental tests. Later, the mass, bulk density, and specific density are determined by using the powdered coal, followed by the porosity analysis. Moving on further, to perform the mineralogical analyses of coal samples, first the proximate analysis is done, and X-ray diffraction (XRD) was used (Bruker Advance D8) to identify the dominant elements and the chemical composition in the coal sample. The SEM-EDX analysis is done to determine the surface textures of the raw coal samples. After obtaining the results from the SEM-EDX, the research is further validated through FTIR analysis to identify unknown materials, additives within polymers, surface contamination on a material, and more. In the last stage, the research can proceed to analyze the caloric value of the coals to study their thermal properties through the bomb calorimeter.

2.1 Materials

The coal that has been the subject of research interest was brought from Mukah, Sarawak, with proper packaging. Prior to any further activities, the coal was open-dried in the laboratory. While to compare all properties and content, a commercial coal (Tesco Brand, Parit Raja) from the available market was obtained as a benchmark. Although coal is a natural fuel that can be exposed to the surrounding environment, proper care should be taken to avoid any effect on the properties of the coal. If the coal is exposed to the surrounding environment after all the sampling process, there are high possibilities for the coal to lose its thermal properties.

2.2 Visual Inspection

The main aim of this step is to analyze the physical appearance of the coal through the image produced by the DSLR camera with a 24.2 megapixel resolution before proceeding with a detailed visualization. To analyze the surface structure of the coal in detail, the microscopic view is considered a very important measure. As mentioned earlier, the DSLR camera has a resolution of 24.2 megapixels only, but the microscope has a resolution up to 100 megapixels and above. Comparatively, it is known that the microscope could give a very detailed surface structure compared to the DSLR camera. For microscopic views up to 1000× magnification, an Olympus optical microscope was used.

2.3 Break Down and Segregate the Samples into Smaller Pieces

In this research, the manual method of crushing the coal sample through the manual hammer method was used. The crushed samples are then sieved for 63 µm size for the mineralogical analysis so that a better mineral identification can be done [7]. The sieving process takes 10 minutes with a vibration frequency of 7 Hz.

2.4 Determination of Bulk Density and Specific Density of the Coal

According to ASTM-D8097, the mass, bulk density, and specific gravity are a few criteria that are taken into account while examining the physical characteristics of the coal. Although the coal's mass is calculated in both the density calculation and its specific gravity, the coal's mass measurement in the latter is more accurate. Equations (1), (2), and (3) can be used to calculate the bulk, specific, and particle densities [8]. Meanwhile, Eq. (4) [7] can be used to determine the coal's porosity.

$$\rho = \frac{A - B}{C} \tag{1}$$

where,

ρ - bulk density (g/m^3)
A - mass of coal filled pycnometer (g)
B - mass of empty pycnometer(g)
C - volume of pycnometer(m^3)

$$C = A - B \tag{2}$$

where,

A - mass of pycnometer, coal and distilled water (g)
B - mass of pycnometer and coal (g)
C - mass of water to use to fill the pycnometer with the coal (g)

$$\rho = \frac{Mass,\ \text{(g)}}{Volume,\ (\text{m}^3)} \tag{3}$$

$$\text{Porosity} = 1 - \left(\frac{\text{Bulk density}}{\text{Particle Density}}\right) \times 100\% \tag{4}$$

2.5 The Proximate Analysis on Coal Samples

The proximate analysis is done to get the ash content, moisture content, and volatile matter. Each piece of content is very much needed so that those values could be used for future analysis. All the percentages of moisture, ash, and volatile matter could be evaluated from Eq. (5) [9, 10].

$$C = \frac{A - B}{A} \times 100\% \tag{5}$$

where,

A - weight of sample used (g)
B - weight of sample after heating (g)
C - % of moisture or ash or weight loss content

2.6 The Spectroscopy Analysis on Coal Sample

The *Bruker-Advanced D8* X-ray Diffraction (XRD) analysis is used to identify mineral phases and elements in coal, which is a powerful analytical technique to identify and characterize unknown mineral matter in coal. This technique requires minimal sample preparation and, in most cases, it provides an unambiguous mineral determination [11]. For XRD analysis, the coal samples were prepared into a coin-like pallet. The 2θ angle used was 0° to 90°.

After going through several visual inspection processes, the coal sample is then fed into the Scanning Electron Microscopy (SEM), a type of microscope that uses an electron beam to illuminate a specimen and produce a magnified image [11]. SEM is most extensively used in coal analysis, and the SEM image analysis can provide valuable information such as particle size, swelling of the particles during conversion, and the structure of char or ash [6].

Fourier Transformation Infrared (FTIR) analysis is an analytical technique that is used to identify organic, polymeric, and, in some cases, inorganic materials. This FTIR analysis method uses infrared light to scan test samples and observe chemical properties. The FTIR spectroscopy could detect the highly dominant matter by producing peaks in either the transmittance or absorbance graph [12]. From the graph, the chemical composition could be identified, and even the chemical structure could be inferred from the FTIR analysis table. KBr FTIR routine was carried out on the coal specimens.

2.7 Evaluating the Thermal Properties of Coal Samples

The thermal properties of the coal sample can only be determined by finding the calorific value (CV). CV can be considered one of the important parameters since coal is mainly mined for combustion applications. Determining the CV, which is a direct indication of the heat content of the coal and the most commonly used benchmark for coal quality and its economic value, Determining the CV was set as the last step in the process because before getting the value, proximate analysis and ultimate analysis needed to be done. The data from previous data analyses will be used as an input in this stage. The chemical content and chemical composition of this coal need to be keyed into the bomb calorimeter.

3. Result and Discussion

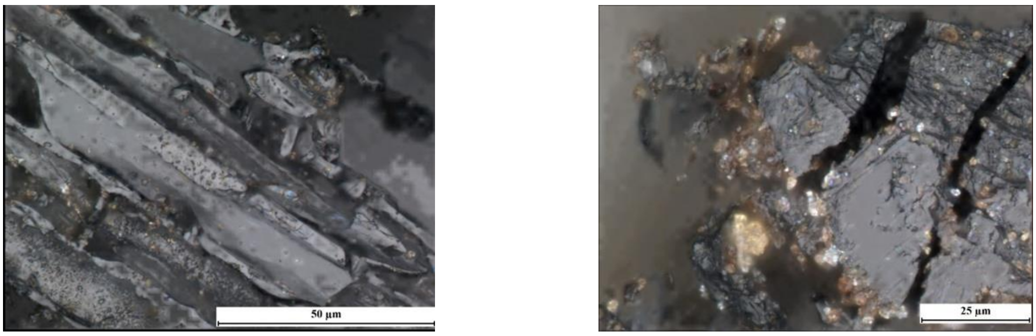
The visual inspection covers the visual analysis of the images that have been taken using a DSLR and a microscope with various lenses. The physical properties that have been covered are the visual inspection of the coals, the mass, the bulk density, and the specific gravity of the coal. The material characterization involves analyzing the material content in the coal with XRD, FTIR, and SEM-EDX screening processes. To find the thermal properties, the caloric value of both coals is identified using the calorimeter.

3.1 Visual Inspection

The visual inspection was done to compare the appearance of both coals. Based on Fig. 3, it can be clearly seen that the two coals can be differentiated with a few specifications. By referring to the following figure, the commercial coal seems to be darker in color, while the Mukah coal is brownish in color. With such an appearance, it gives the idea that Mukah coal should fall between the lignite and bituminous categories. The coal in the lignite category should be brownish in appearance and powdery in texture. On the other hand, the bituminous category states that the coal in it should have a shiny surface and be crushable due to its softness. Comparatively, this Mukah coal meets both the specifications of both categories in that it has a brownish, powdery, and shiny surface. Extensively, it is crushable due to its softness.

Fig. 3 - The commercial coal is on the left and the Mukah coal is on the right

Besides, the analysis can be done by just referring to the two microscopic views themselves, which may give a general idea of the elements that are in the coal. After going through various microscopic views, there were lots of interesting elements that needed to be analyzed. The visual analysis can be done by just referring to the two microscopic views themselves, which may give a general idea of the elements that are in the coal (Fig. 4).



(a) **(b)**

Fig. 4 - The microscopic view at 1000 × magnification of (a) commercial coal, and; (b) Mukah coal

Fig. 4(a) is the microscopic view of the commercial coal at 1000× magnification, where it can be seen that the microstructure is more of a wood-like axed structure. Fig. 4(b) shows the microscopic view of Mukah coal at 1000× magnification. It can also be seen that some other elements or impurities (the bright phase) dissipated between the coal. XRD and EDX had been used to verify the primary findings.

3.2 Determining the Physical Properties of Coals

From the densities evaluation of both Mukah and commercial coals, a simple comparison can be made, as shown in Table 4. It was found that the Mukah coal recorded higher bulk and particle densities as compared to the commercial coal. Since Mukah coal was obtained as it is without any post-production processes, the coal obviously contained other minerals besides hydrocarbon compounds. On the contrary, before entering the market, commercial coal undoubtedly went through certain production stages that reduced the amount of non-hydrocarbons and also caused a decrease in its porosity. As a result, the densities of commercial coal were very different.

Table 4 - The overall densities of both samples

Parameters	Coal Type	
	Mukah	**Commercial**
Bulk density (g/cm^3)	0.5103	0.2790
Particle density (g/ml)	0.6798	0.393
Porosity (%)	24.93	29.00

3.3 Determining the Thermal Properties of Coal Through Proximate Analysis

It is found that the Mukah coal sample records 13.60% of moisture content, and 7.38% of moisture content was recorded in the commercial coal sample (Table 5). The high percentage of moisture in coal is generally due to the vegetation process from which coal was formed, where the water content and varying amounts of this water were still present at various stages of the coalification process. Based on Table 5, it seems that the Mukah coal has a higher moisture content compared to the commercial coal. This higher moisture content may occur due to the raw content of Mukah coal, where this coal is directly used for combustion right after mining without any preparation process.

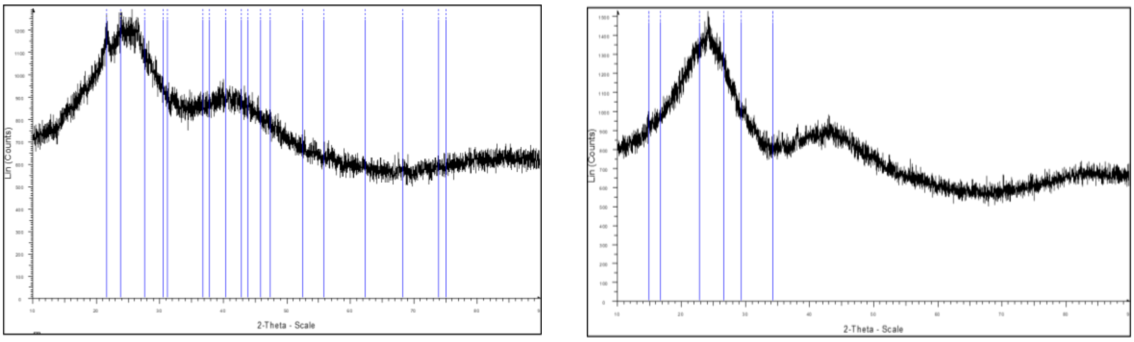
Table 5 - The overall proximate analysis results

Proximate Analysis Element	Coal Type	
	Mukah	**Commercial**
Ash content (%)	10.0	6.0
Moisture content (%)	13.60	7.38
Volatile matter (%)	85.4	91.62

Based on the above obtained data, it can be seen that the Mukah coal sample has a higher ash content compared to the commercial coal. Generally, coal ash is considered silicon dioxide or silica (SiO2) based on the chemical formula. It will be further proved during the XRD analysis. For the time being, by comparing the above data, it can be estimated that the silicon content will be higher in Mukah coal compared to commercial coal. These findings can somehow give an idea that it is possible that the Mukah coal should have a high content of silicone in it as it is mined directly from the soil, which is high in silicone content naturally. It can also be found that the volatile matter content in Mukah coal is lower compared to commercial coal.

3.4 Determining the Mineral Content in the Coal

Based on Fig. 5, from the two XRD graphs, it can be seen both samples are in an amorphous state. The carbon that was detected in the Mukah sample has the ICDD number of 00-046-0945 and the carbon that was detected in commercial coal has the ICDD number of 00-050-0926. By analyzing the peaks that were generated from the analysis, it can be seen that in both graphs, the carbon content represents the peak. Since Mukah coal is raw coal, its carbon has a different crystallographic arrangement since other impurities are also present in the coal. The commercial coal, however, has gone through various processing and treatment stages that resulted in a purer carbon content in graphite structures. Therefore, it gives an idea that carbon is the most dominant element in both coal samples. This analysis will be further proved in EDX analysis.



(a) **(b)**

Fig. 5 - The XRD result of (a) Mukah coal, and; (b) commercial coal

The EDX analysis is basically element identification. The parameters in EDX were set based on the required parameters for finding the calorimeter. The elemental parameters that were set were carbon, silicon, oxygen, gold (conductive coating), and sulfur, which are the required parameters to run the caloric meter to find caloric value. Basically, three spectrums were set for each sample so that the analysis could cover the overall element content in the samples. The average percentage of element content from all three spectrums was considered for further analysis, which is for caloric value identifications. Table 6 illustrates a clear comparison of element content in both Mukah and commercial coals.

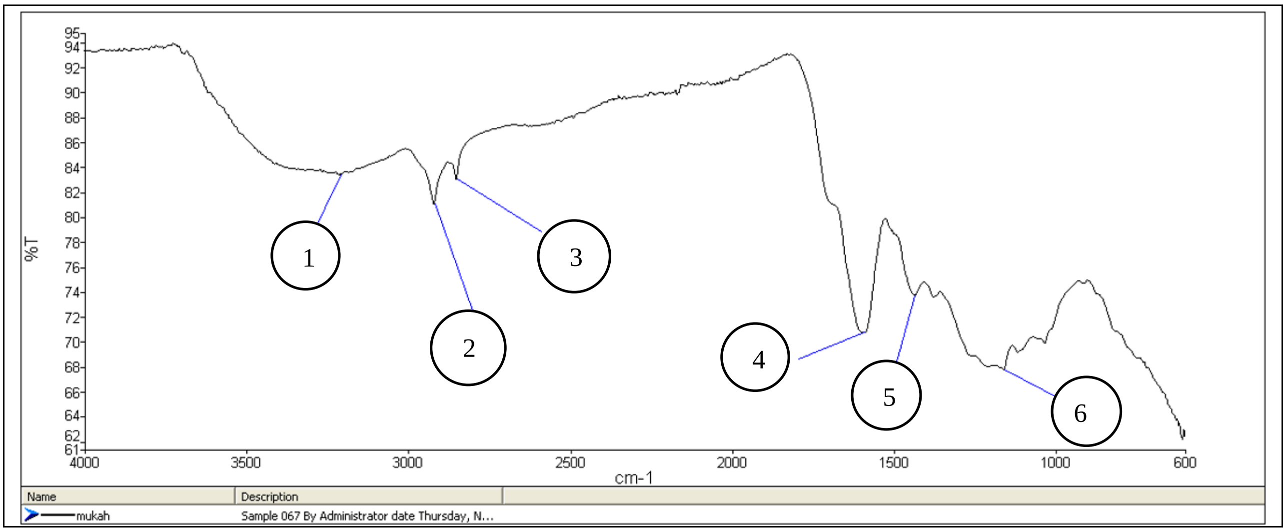
Table 6 - Mineral content in Mukah and commercial coals

Elements	Mukah (wt%)	Commercial (wt%)
Carbon	65.80	76.00
Oxygen	27.67	20.00
Silicon	0.25	0.09
Gold (coating)	5.67	3.83
Sulphur	0.60	0.04
Total	**100.00**	**100.00**

It is found that the carbon content in commercial coal is higher compared to Mukah coal, while the XRD analysis shows that carbon is the most dominant element in the Mukah coal sample compared to the commercial coal sample. These differences in analysis may occur due to the spectrum's location. Certain spectrum may have different, high elemental content. Moreover, the commercial coal goes through a few processes to be used as combustion material, where some elements may have been used up during the process and left some residues that have a higher content. Carbonization in the making of charcoal, which in this research was referred to as commercial coal, is initiated in a closed space by heating a pile of wood under low oxygen conditions.

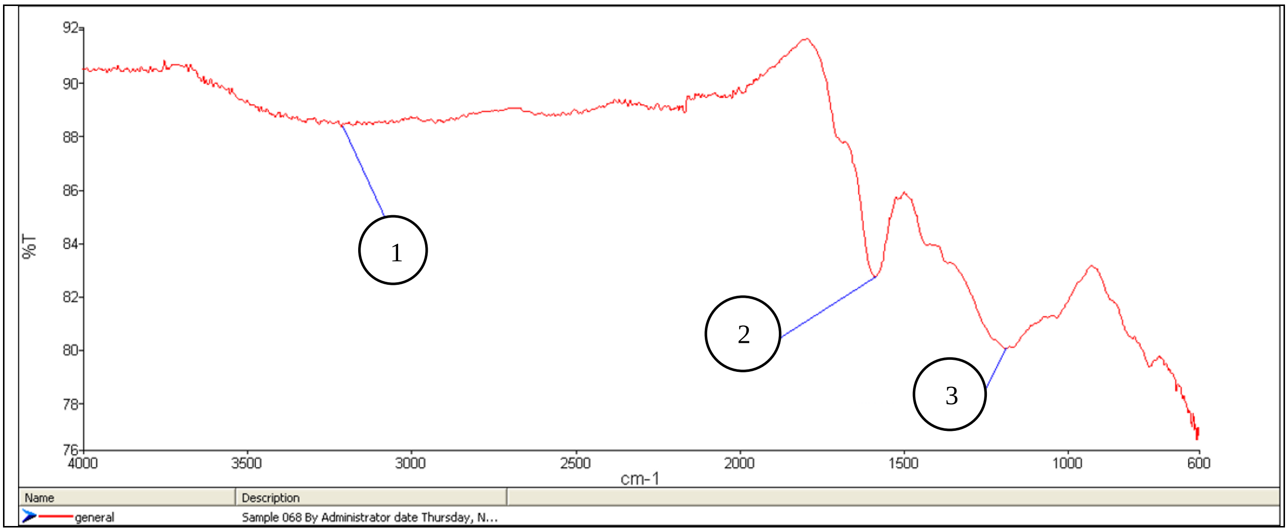
High temperatures induce the absorption of heat, which leads to the decomposition of biomass, separating it into volatile gases, vapour, and solids [13]. With such a charcoal production process, it is possible for the commercial coal to have a higher carbon content than the Mukah coal. This situation is relatively different for Mukah coal, where its consumption is right from the raw material. Based on the data presented above, it is clear that the silicon and oxygen content of the Mukah sample is higher than that of the commercial coal sample. This data further gives a better perspective on the ash content in the samples. As mentioned earlier, the ash's chemical formula is silicon dioxide or silica ($SiO2$). Previously, during the proximate analysis of the ash content, it was found that the Mukah coal sample has a higher ash content compared to the commercial coal, and this has been further proven through this EDX analysis. Sulfur's elemental content also seems to be higher in the Mukah coal sample compared to the commercial one. Based on the FTIR analysis in Table 7 and 8, the carbon content in the Mukah coal sample is less than that in the commercial sample. This had again proven the assumption that was made earlier in the EDX analysis. The particular element that needs more attention is hydrogen. Basically, coal is known as a hydrocarbon. It means the composition of hydrogen is relatively important to be considered as the element that could contribute to the thermal properties of the coal.

Table 7 - FTIR analysis of Mukah coal



No.	Wavenumber (1/cm), Transmittance Percentage (%)	Absorption range (1/cm)	Appearance	Group	Compound Class
1	3210.82, 83.47	3300-2500	strong, broad	O-H stretching	Carboxylic acid
2	2919.74,81.12	3000-2840	medium	C-H stretching	Alkane
3	2850.68,83.12	3000-2840	medium	C-H stretching	Alkane
4	1590.98,70.82	1650-1566	medium	C=C stretching	Aromatic
5	1435.74,73.79	1440-1395	medium	O-H bending	Carboxylic acid
6	1158.78,67.86	1205-1124	strong	C-O stretching	Tertiary alcohol

Table 8 - FTIR analysis of Commercial coal



No.	Wavenumber (1/cm), Transmittance Percentage (%)	Absorption range (1/cm)	Appearance	Group	Compound Class
1	3211.16, 88.39	3300-2500	strong, broad	O-H stretching	Carboxylic acid
2	1585.24,82.77	1650-1566	medium	C=C stretching	Aromatic
3	1188.78,80.08	1205-1124	strong	C-O stretching	Tertiary alcohol

The percentage of hydrogen composition is higher in the Mukah coal sample compared to the commercial coal. This composition may become the influential factor that could affect the thermal properties of both coals since the other two elements do not have much difference in their composition in their respective coal samples. This could only be further proved by finding the caloric value of both coal samples, which would be analyzed in the last stage of this research.

3.5 Determining the Caloric Value of the Coal

Based on all the needed parameters, it is found that the Mukah coal sample records a low caloric value of 22.20 MJ/kg compared to the standard value of 27.00 MJ/kg. It may be due to the higher moisture content in it. The moisture content does really affect the thermal properties. Since the commercial coal sample has gone through proper prediction processes, it shows better thermal properties.

4. Conclusion

In a nutshell, all the objectives set forth for the research had been achieved. Mukah coal exhibited enormous potential to be applied in various sectors, from agriculture to power plants. In spite of the proofs obtained from this work, Mukah coal still has unlimited aspects that must be further researched.

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