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Geochemical Characteristics of the Cretaceous Emewe–Efopa Coal in the Northern Anambra Basin of Nigeria

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Abstract*: Geochemical analysis has been carried out on coal samples from Emewe–Efopa coal in the northern Anambra Basin of Nigeria. The study was carried out mainly to determine the geochemical characteristics of the coal and its industrial potentials. Results of proximate analysis indicated that the coal contains 12.63% moisture, 5.71 % ash, 46.65 % volatile matter and 35.01 % fixed carbon. Ultimate analysis results also revealed that the coal consists of 60.99 % carbon, 5.37 % hydrogen, 1.25 % nitrogen, 13.01 % oxygen, 1.06 % sulphur and 0.013 % phosphorus. The average heating value of the coal is 11,084 Btu/1b while its free swelling index was calculated at 0.0. The results led to the conclusion that the coal is only appropriate for electricity generation, heating boilers and ovens in industrial process heating, manufacturing organic chemicals and production of gas and automotive fuel.*

Keywords: *Emewe–Efopa coal, proximate, ultimate, calorific value, free swelling index*

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1.0 Introduction

Coal is one of the most abundant fossil fuels in Nigeria and is a primary source of electricity in some countries including USA, China, India and South Africa. In spite of the large deposits of coal in various parts of Nigeria, the challenge of sustaining economic value of this valuable resource lies in the management profile that is directed towards its exploitation and utilization.

Apart from sparsely reported occurrences of lignites and minor sub-bituminous coals in the Sokoto Basin (Kogbe, 1989), in the Mid-Niger (Bida) Basin (Adeleye, 1989) and in the Dahomey Embayment (Reyment, 1965), all the coal deposits of Nigeria occur in the Benue Trough and the Anambra Basin (Fatoye *et al*., 2020).

Coal was first discovered in Nigeria in Udi near Enugu within the Anambra Basin in 1909 by the Mineral Survey of Southern Nigeria (Orajaka *et al*., 1990 and Famuboni, 1996). Between 1909 and 1913, more coal seams were discovered in Enugu and Ezimo, Enugu State; Orukpa, Benue State; Odokpono, Okaba and Ogboyaga, Kogi State.

These seams belong to the Mamu Formation (Lower Coal Measures) of Middle Campanian – Late Maastrichtian age (Simpson, 1954). Coal seams of the Nusukka Formation (Upper Coal Measures) of Late Maastrichtian – Late Paleocene age outcrop at Inyi west of the Enugu escarpment were also discovered in the late nineties (De-Swardt and Casey, 1963).

Coal mining commenced in Nigeria in 1916 at Enugu in a drift mine. In 1950, the Nigerian Coal Corporation (NCC) was established to oversee the exploration, development and mining the coal resources. Between 1950 and 1959, coal production in the Enugu mines increased annually from 534,429 tones to a peak of 919,883 tonnes (Famuboni, 1996). During this period of growth, coal played a significant role in Nigeria's economic development. Coal was mainly utilized by the Nigerian Railway

Corporation (NRC) to operate its locomotives, for electricity generation by the Electricity Corporation of Nigeria (ECN), which later became the National Electric Power Authority (NEPA) and for the firing of kilns by the Nigerian Cement Company (NIGERCEM) at Nkalagu.

But total dependence on oil and oil-derived foreign exchange in planning the nation's economy resulted in the relegation of coal to the background. However, the Federal Government is recently planning to revitalize the coal mining industry and expand power generation by attracting foreign companies to explore and apply coal in generating electricity.

Currently, it has been confirmed that there is a large deposit of coal beds within the sedimentary succession of the Anambra Basin of Nigeria (Obaje, 1994) especially the Mamu Formation in the Emewe–Efopa area of the Basin. However, literature is scanty on the geochemical properties of this coal deposit. Geochemical analysis of coal can reveal vast volume of information about the quality of coal and possible utilization (Zhou *et al*., 2019).

Therefore, the present study is aimed at assessing the geochemical characteristics of Emewe–Efopa coal in order to ascertain the potential relevance of the coal to possible industrial usages.

2.0 Materials and Methods

2.1 Study Location

Emewe–Efopa coal deposit is situated on Latitude 7^0 30' 36.4" N and Longitude 6^0 50' 15.4" E. It is located off Abocho town along Anyigba – Abocho – Dekina road in Dekina Local Government Area of Kogi State (Fig. 1). Drainage is generally that of the dendritic pattern. The area is well drained with rivers and their tributaries which occupy wide valleys. Most of these rivers are tributaries to the Anambra River. The area is generally undulating lowland with a few isolated hills. It has an average elevation of 186m above sea level.

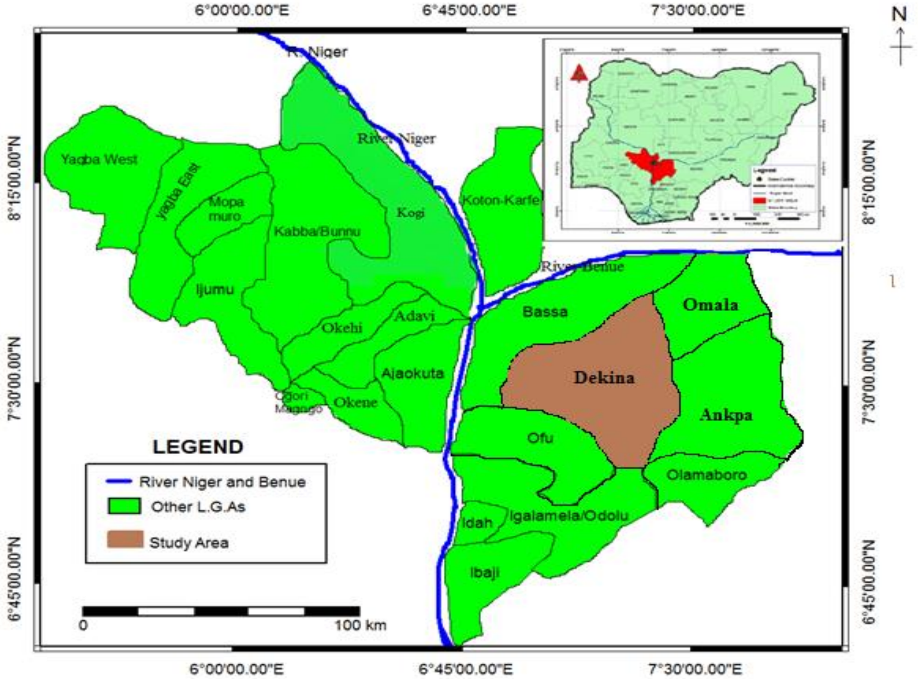

Fig. 1: Location map of the study area

2.2 Regional geological setting

The study area lies within the Anambra Basin of Nigeria. The structural setting and general geology of the Anambra Basin have been widely reported (Nwajide and Reijers, 1996; Obaje *et al*., 1999; Umeji, 2005). Sedimentation in the Anambra Basin commenced with the Campanian – Maastrichtian marine and paralic shales of the Nkporo Formation (Fig. 2), overlain by the Early – Late Maastrichtian coal measures of the Mamu Formation, comprising paralic sandstones, mudstones and coals. The Middle – Late Maastrichtian fluviodeltaic sandstones of the Ajali Formation lie on the Mamu Formation and constitute its lateral equivalents in most places. In the Paleocene, the marine shales and paralic coaly sequence of the Nsukka Formation were deposited to complete the succession in the Anambra Basin (Umeji, 2005).

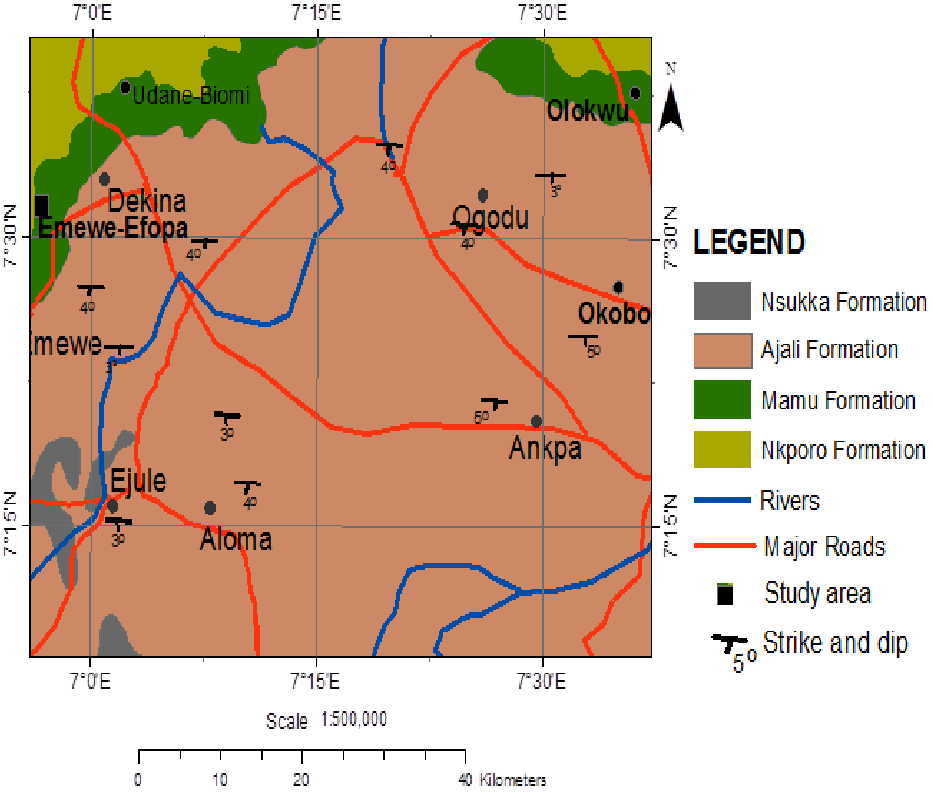

Fig. 2: Geological map of the study area

2.3 Sampling

Ten coal samples were collected from Emewe–Efopa coal deposit. The samples were taken from the coal outcrops. Samples collected were kept in an airtight polyethylene bags prior to analyses. The coal samples were pulverized and sieved to pass through a 60 mm sieve size. All analytical determinations were done according to the American Standard for Testing Materials (ASTM) 1992 standards methods. All sample analyses were carried out at Mineral Laboratory, Kentucky, USA.

2.4 Proximate Analysis

Chemical composition of the coal was defined in terms of its proximate analysis which included analysis for moisture, volatile matter, ash, and fixed carbon.

2.4.1 Determination of moisture content

Exactly 1.00 g of the pulverized sample of each coal was placed in separate pre-weighted silica crucibles and subjected to a temperature of 105^{0}C for 1 hour in the absence of air, until a constant weight was attained.

2.4.2 Determination of ash content

In order to determine the ash content of the coal samples, 1.00 g each of the pulverized samples were weighted into three separate platinum crucibles and subjected to a temperature of 750 ^{0}C in a muffle furnace for about 2 hours until a constant weight was attained.

2.4.3 Determination of volatile matter

1.00 g of pulverized sample of each coal was weighted and covered in a 10ml platinum crucible. The same was subjected to a temperature of 950 ^{0}C in a muffle furnace for 7 minutes.

2.4.4 Determination of fixed carbon

The fixed carbon was estimated as the difference between 100 and the total sum of moisture, ash and volatile.

Fixed Carbon (%) = 100 – (% moisture content + % ash content + % volatile matter content).

2.5 Ultimate Analysis

Geochemical composition of the coal was defined in terms of its ultimate analysis. Ultimate (Elemental) analysis is dependent on quantitative analysis of various elements present in the coal samples, such as carbon, hydrogen and oxygen (the major components) as well as nitrogen, sulphur and phosphorus.

2.5.1 Determination of carbon and hydrogen

1.00 g of coal was burnt in a current of oxygen in order to convert the C and H to CO_2 and H_2O respectively. The products of combustion (CO_2 and H_2O) were passed over weighted tubes of anhydrous $CaCl_2$ and KOH which absorbed H_2O and CO_2 respectively. The increase in the weight of $CaCl_2$tube was used as an estimate for weight of water (H_2O) formed while increase in the weight of KOH tube represented the weight of CO_2 formed.

2.5.2 Determination of nitrogen

Nitrogen was determined by Kjeldahal's method. 1.00 g of pulverized coal was heated with concentrated H_2SO_4 in the presence of potassium sulphate and copper sulphate in a long necked flask thereby converting nitrogen of coal to ammonium sulphate. When clear solution was obtained it was treated with 50 % NaOH solution. The ammonia thus formed was distilled over and absorbed in a known quantity of standard sulphuric acid solution. The volume of unused H_2SO_4 was then determined by titrating against standard NaOH solution. Thus, the amount of acid neutralized by liberated ammonia was determined.

2.5.3 Determination of oxygen

Oxygen was determined by subtracting the amount of the other elements, carbon, hydrogen, nitrogen, sulphur, moisture and ash from 100%.

% of oxygen in coal = 100 – (% C + % H + % N + % S + % M + % A)

2.5.4 Determination of sulphur

A 1.00g sample of coal of 0.2mm particle size was heated with Eschka mixture (which consists of 2 parts of MgO and 1 part of anhydrous Na_2CO_3) at 800^0C. After burning amount of sulphur present in the mix was retained as oxides and it was precipitated as sulphate. The sulphate formed was precipitated as $BaSO_4$ (by treating with $BaCl_2$). The percentage of sulphur in coal was calculated from the weight of coal sample taken and weight of $BaSO_4$ precipitate formed.

2.5.5 Determination of phosphorus

Phosphorus was determined by treating 1.00 g of the coal ash with a hot mixture of HNO_3, H_2SO_4 and HF acids. This volatilized the silica and dissolved the phosphorus to precipitate a complex phospho-molybdate from which the phosphorus content was estimated.

2.6 Calorific Value Analysis

A bomb calorimeter was used to measure the calorific value of the coal. Electrical energy was used to ignite the coal; as the coal was burning, it heated up the surrounding air, which expanded and escaped through a tube that leads the air out of the calorimeter. When the air was escaping through the copper tube it also heated up the water outside the tube. The change in temperature of the water was then accurately measured with a thermometer. This reading, allowed for calculating calorie content of the coal.

2.7 Determination of free swelling index

10.00 g of finely grounded coal sample was weighed into a dry platinum crucible. The crucible was placed in a muffle furnace and the temperature was raised to 800 ^{o}C until all volatiles were driven off. The crucible was removed from the furnace and allowed to cool. The cross section of the coke "button' was then compared to a series of standard profiles (chart) to determine the free swelling index.

3.0 Results and Discussion

Results obtained from proximate analysis of Emewe–Efopa coal samples are recorded in Table 1. The moisture content was observed to vary from 11.87 % in sample 3 to 13.17 % in sample 6 (Table 1). Moisture is an undesirable constituent of coals because it reduces the heating value (water does not burn!) and its weight adds to the transportation costs of coal. Moisture content of a coal provides indices for ranking coals. The lower the moisture content of a coal, the higher its rank and vice versa. The moisture content required for good coking coal is 1.5 % (Obaje, 1997). Therefore, the value recorded in Emewe–Efopa coal is above the stipulated rating for coking coal. However, Gunn *et al*. (2012) recommended maximum of less than 30 % moisture content for thermal coals indicating that the studied coal with average moisture content of 12.63% is suitable for generation of electricity and heating for manufacturing of cement, ceramics, glass, paper, bricks, etc.

The ash content ranged from 5.00 % in sample 5 to 6.31 % in sample 9. Lower ash content is an essential requirement for coke making coals, because some of the ash would end up in the coke on carbonization and in the blast furnace (Akpabio, 1998). The lower the ash content of a coal, the better its application as a source of fossil fuel especially in the steel industry (Wessiepe, 1992). Ash reduces plasticity and determines the behaviour of slag and fouling in combustion chamber (ASTM, 1987).

Table 1: Proximate analysis results of Emewe–Efopa coal samples

Sample Number	Moisture Content (%)	Ash Content (%)	Volatile Matter (%)	Fixed Carbon (%)	Total (%)
Emewe–Efopa 1	12.34	5.48	46.79	35.39	100.00
Emewe–Efopa 2	12.91	5.94	46.52	34.63	100.00
Emewe–Efopa 3	11.87	6.12	45.65	36.36	100.00
Emewe–Efopa 4	12.72	5.72	46.47	35.09	100.00
Emewe–Efopa 5	13.04	5.00	48.68	33.28	100.00
Emewe–Efopa 6	13.17	5.23	48.79	32.81	100.00
Emewe–Efopa 7	12.66	6.01	45.82	35.51	100.00
Emewe–Efopa 8	12.88	5.54	45.63	35.95	100.00
Emewe–Efopa 9	11.98	6.31	45.58	36.13	100.00
Emewe–Efopa 10	12.73	5.75	46.57	34.95	100.00
Average	**12.63**	**5.71**	**46.65**	**35.01**	**100.00**
X	**15.10**	**12.35**	**46.10**	**26.45**	**100.00**
Y	**4.31**	**0.20**	**31.26**	**64.23**	**100.00**
Z	**3.15**	**1.32**	**21.63**	**73.90**	**100.00**

X: Saar (Germany) sub-bituminous coal (after Jensen and Bateman, 1979),
Y: Newcastle (England) bituminous coal (after Jensen and Bateman, 1979),
Z: South Wales (Britain) anthracite (after Jensen and Bateman, 1979)

The high ash content is also an indication of low degree of coalification and hence immaturity of the coal. An ash content of less than 10% is recommended for good coking coals (Akpabio *et al*., 2008; Bustin *et al.,* 1985; Averitt, 1974). Maximum of 10 – 20% is recommended by Thomas (2002) in coking coals, as higher ash contents reduce the efficiency in the blast furnace. In a steam coal, high ash content will effectively reduce its calorific value. Recommended maximum ash content for steam coals serving as pulverized fuel is around 20 % (Thomas, 2002). Though the ash content of the studied coal is within the less than 10% recommended for good coking coals but its high moisture content makes it unsuitable for coke making. However, the coal is appropriate for electricity generation and heating for manufacturing processes. The cement, ceramics, glass, paper and bricks industries can use it for this purpose.

The volatile matter content of the coal varied from 45.58% in sample 9 to 48.79 % in sample 6 (Table 1). Volatile matter represents the components of coal, except for moisture which are liberated at high temperature in the absence of air. Volatile matter includes light hydrocarbon compounds such as carbon dioxide (CO_2), methane (CH_4), etc. They were produced by the decomposition of each layer of dead plant material by aerobic or oxygen-requiring bacteria during coalification. Volatile matter also includes hydrogen, oxygen, nitrogen, sulphur, phosphorus and carbon that are lost in the form of gases and vapour on carbonization. The volatile matter apart from its use in coal ranking is one of the most important parameters used in determining their suitability and applications (U.S. Energy Information Administration, 2008; Chen and Ma, 2002). In coke production, volatile matter range of 20 – 35% is expected (Thomas, 2002). In pulverized fuel firing for electricity generation, most boilers are designed for a minimum volatile matter of 20 – 25% (Thomas, 2002). In stoker firing for electricity generation, the volatile matter limits recommended are 25 – 40%. Therefore, the average value of 46.65% volatile matter recorded in Emewe–

Efopa coal is above the stipulated rating for coking coal. However, the coal is appropriate for electricity generation and heating for manufacturing processes. The fixed carbon content of the coal ranged from 32.81 % in sample 6 to 36.36 % in sample 3 (Table 3). The coal is characterized by low fixed carbon content compared with high rank coals (Table 3). The fixed carbon content of a coal has a direct relation with its moisture and volatile matter, therefore, the low fixed carbon content in the coal may be attributed to its high moisture and volatile matter. Fixed carbon content determines the coke yield of coal samples (Diez *et al*., 2002 and Schobert, 1987). High carbon content is essential for coke making coal because it is the mass that forms the actual coke on carbonization (Diez *et al*., 2002). Maximum of 46 – 86 % is recommended by Lowry (1945) in coking coals. Emewe–Efopa coal with low average value of 35.01 % fixed carbon content is not coking. However, it could be utilized in thermal power plants and other small industries for combustion processes.

Results of proximate analysis generally revealed that the studied coal is characterized by high moisture, low ash, high volatile matter and low fixed carbon contents. Comparing these characteristics with other coals (X, Y and Z in Table 1), the studied coal is similar to Saar (Germany) sub-bituminous coal but contrast with Newcastle (England) bituminous coal and South Wales (Britain) anthracite all reported by Jensen and Bateman (1979) thereby placing Emewe – Efopa coal in sub-bituminous rank.

Table 2: Ultimate analysis results of Emewe–Efopa coal samples

Sample Number	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Sulphur (%)	Phosphorus (%)	Total (%)
Emewe–Efopa 1	59.88	5.30	1.38	13.00	1.01	0.014	80.58
Emewe–Efopa 2	60.60	5.31	1.22	12.99	1.03	0.011	81.16
Emewe–Efopa 3	61.37	5.43	1.27	13.03	1.09	0.014	82.20
Emewe–Efopa 4	61.77	5.12	0.90	12.10	1.04	0.012	80.94
Emewe–Efopa 5	61.68	5.21	1.41	12.80	1.05	0.013	82.16
Emewe–Efopa 6	59.97	5.66	1.32	13.73	1.11	0.014	81.80
Emewe–Efopa 7	61.20	5.49	1.52	13.55	1.00	0.013	82.77
Emewe–Efopa 8	61.83	5.02	1.30	12.80	1.10	0.014	82.06
Emewe–Efopa 9	60.85	5.61	0.97	12.80	1.11	0.012	81.35
Emewe–Efopa 10	60.75	5.55	1.21	13.30	1.06	0.013	81.88
Average	**60.99**	**5.37**	**1.25**	**13.01**	**1.06**	**0.013**	**81.69**
X	**67.60**	**4.80**	**1.20**	**17.70**	**0.80**	**0.06**	**92.16**
Y	**83.47**	**6.68**	**0.59**	**8.00**	**0.20**	**0.04**	**98.98**
Z	**91.44**	**3.36**	**0.09**	**2.70**	**0.09**	**0.03**	**97.71**

X: Wyoming (USA) sub-bituminous coal (after Spath and Amos, 1995)

Y: Newcastle (England) bituminous coal (Jensen and Bateman, 1979)

Z: South Wales (Britain) anthracite (after Jensen and Bateman, 1979)

The observed carbon content of the coal varied from 59.88 % in sample 1 to 61.83 % in sample 8 (Table 2) while hydrogen ranged from 5.02% in sample 8 to 5.66 % in sample 6. Carbon and hydrogen are the principal combustible elements in coal. Maximum of 75 – 90 % carbon and 4.5 – 5.5 % hydrogen is recommended by Lowry (1945) in coking coals. Based on carbon content, the coal has no coking ability.

The measured nitrogen content of the coal varied from 0.90 % in sample 4 to 1.52 % in sample 7 (Table 2). Coals should not as a rule have nitrogen contents of more than 1.5 – 2.0 % because of the NOx emissions (Thomas, 2002). Maximum of 1.0 – 1.5 % is recommended by Lowry (1945) in coking coals. The oxygen content of the coal ranged from 12.10 % in sample 4 to 13.73% in sample 6 (Table 2). Oxygen is a component of many of the organic and inorganic compounds in coal as well as the moisture content. When the coal is oxidized, oxygen may be present in oxides, hydroxides and sulphate minerals and as organic material. The lower the oxygen content of a coal the better the coal. As oxygen content increases, moisture holding capacity increases and caking power decreases. It should be remembered that oxygen is an important indicator of rank in coal. Maximum of 5 – 20 % is recommended by Lowry (1945) in coking coals while Gunn *et al*. (2012) proposed maximum 16 – 20 % for thermal coals. Though the coal is moderate in nitrogen and oxygen contents yet it is not suitable for the production of coke for metallurgical processes (such as iron and steel manufacture) because of its low carbon content which is a principal combustible element. However, the coal is appropriate for electricity generation and heating for manufacturing processes. The cement, ceramics, glass, paper and bricks industries can use it for this purpose.

The sulphur content of the coal varied from 1.00 % in sample 7 to 1.11% in samples 6 and 9 (Table 2) while the phosphorus content ranged from 0.011% in sample 2 to 0.014% in samples 1, 3, 6 and 8. Bustin *et al*. (1985) recommended less than 1.0 % sulphur for coke-making coal. According to Thomas (2002), the total sulphur content in steam coals used for electricity generation should not exceed 0.8 – 1.0 %; the maximum value however depends upon local emission regulations. In the cement industry, a total sulphur content of up to 2.0 % is acceptable, but a maximum of 0.8 % is required in coking coals, because higher values contribute to producing brittle steel, causes slagging and fouling in the furnace thereby impeding its functions and causes corrosion of the furnace. Phosphorus is another element with adverse effect on iron quality. Unlike sulphur, its final placement in the iron product is not easily controlled by adjustment of slag volume. Care must therefore be taken that the coals used in coke-making have a low initial phosphorus content. Zimmerman (1979) stated 0.05 % to 0.06 % as a safe limit while Gray *et al*. (1978) quoted a lower limit of 0.03%. According to Thomas (2002) coking coals should have a maximum phosphorus content of 0.1 %. The sulphur content of the coal is high therefore making it unsuitable for generation of substantial heat for the working of blast furnace for iron smelting. However, the coal is appropriate for electricity generation and heating for manufacturing processes.

Results obtained from ultimate analysis indicated that the studied coal is also characterized by low carbon, low oxygen and high sulphur contents. Comparing these characteristics with other coals (X, Y and Z in Table 2), the studied coal is similar to Wyoming (USA) sub-bituminous coal reported by Spath and Amos (1995) but contrast with Newcastle (England) bituminous coal and South Wales (Britain) anthracite reported by Jensen and Bateman (1979) thereby placing Emewe–Efopa coal in sub-bituminous rank.

Table 3: Calorific value results of Emewe – Efopa coal samples

Sample Number	**Calorific Value**	
	(Btu/1b)	**(Kj/Kg)**
Emewe–Efopa 1	11,212	26079.112
Emewe–Efopa 2	10,955	25481.330
Emewe–Efopa 3	11,775	27388.650
Emewe–Efopa 4	11,197	26044.222
Emewe–Efopa 5	10,786	25088.236
Emewe–Efopa 6	9,851	22913.426
Emewe–Efopa 7	11,413	26546.638
Emewe–Efopa 8	10,810	25144.060
Emewe–Efopa 9	11,511	26774.586
Emewe–Efopa 10	11,330	26353.580
Average	**11,084**	**25781.384**
X	**8,683**	**20196.658**
Y	**12,000**	**29540.200**
Z	**15,700**	**36518.200**

X: Wyoming (USA) Sub-bituminous coal (after Spath and Amos, 1995),
Y: San Pedro (USA) Bituminous coal (after Warwick and Hook, 1995),
Z: Barakar (India) Anthracite (after Sethi, 2014)

The calorific value of the coal varied from 9,851Btu/1b in sample 6 to 11,775Btu/1b in sample 3 (Table 3). Mineral matter, moisture and ash contents of a coal help in determining its calorific (heating) value. The less these contents the better the calorific value. Bustin *et al*. (1985) recommended 14,499 Btu/1b for good metallurgical coal while Wendy (2017) proposed that the calorific value should not be less than 8,500 Btu/1b calorific value for heating. Based on these recommendations, the studied coal is not suitable for metallurgical purposes. However, it is suitable for electricity and combustion purposes. The calorific value of Emewe–Efopa coal is similar to the value reported for Wyoming (USA) sub-bituminous coal by Spath and Amos (1995) but contrast with those reported for San Pedro (USA) bituminous coal and Barakar (India) anthracite by Warwick and Hook (1995) and Sethi (2024) respectively thereby placing Emewe–Efopa coal in sub-bituminous rank.

Free swelling index (FSI) is a measure of the plasticity and devolatilisation characteristics of a coal. The higher the FSI for a coal, the more suitable is the coal for coke manufacture. Values of FSI greater than 4 are recommended for coal required for coke manufacturing (Blackmore, 1979). Based on this recommendation, the studied coal with zero (0) FSI is unsuitable for coke production. However, Blackmore (1979) stated that the higher the FSI for a steam coal, the lower the efficiency of combustion. This implies that the Emewe–Efopa coal is good for steam coal suitable for generation of electricity and for heating in the manufacturing industries.

4.0 Conclusion

Proximate, ultimate and calorific value analyses and free swelling index test revealed that Emewe–Efopa coal has high moisture, low ash, high volatile matter, low carbon, low oxygen, high sulphur, low calorific values and zero (0) free swelling index. The coal samples are of low quality, non-coking and sub-bituminous, hence, has little capacity for the generation of substantial heat requires for the operation of the blast furnace for iron smelting. However, it is good for electricity generation. The coal is also appropriate in heating for manufacturing processes.

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