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Characterisation of the Fuel Properties and Energy Recovery Potential of Obomkpa Coal from Delta State in Nigeria

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Abstract

This paper examined the fuel properties and energy recovery potential of the newly discovered Obomkpa (BMK) coal from Delta State in Nigeria. Consequently, the physicochemical, calorific, and thermal properties of BMK were characterised through ASTM standards and techniques for determining elemental, proximate, calorific, and thermal degradation properties. The result revealed BMK has high compositions of carbon, oxygen, volatiles, fixed carbon, ash content and higher heating value (HHV). Based on its HHV of 19.66 MJ/kg, BMK could potentially be ranked as either Lignite A or Sub-bituminous C coal. Thermal analysis revealed BMK experienced high mass loss (M_L) under the oxidative (combustion) and non-oxidative (pyrolysis) conditions examined in the study. The mass loss (M_L) ranged from 59.27% to 76.56%, whereas the residual mass (R_M) was between 23.44% and 40.73% under oxidative (combustion) and non-oxidative (pyrolysis) conditions. Thermal degradation occurred in three (3) stages; drying (30°C to 200°C), devolatilization (200°C–500°C and 600ºC), and finally, the degradation of coke into ash. Furthermore, the DTG peaks and temperature profile characteristics (TPCs) indicate the oxidative (combustion) is more thermally efficient relative to the non-oxidative (pyrolysis) process. In conclusion, BMK could be a prospective feedstock for coal-fired electricity production or the production of cement, iron ore or steel.

Keywords: *Obomkpa coal; Organic macerals; Vitrinite; Pyrolysis; Combustion; Nigeria.*

1. Introduction

Coal is an organic sedimentary rock formed from the metamorphic reactions of peat and other plant or animal residues in the earth's crust [1]. Consequently, coal is regarded as one of the most important fossil fuels particularly due to its low processing costs, widespread availability, and geographical distribution on the planet [2]. In addition, the high combustibility of coal due to its high contents of carbon, fixed carbon, and higher heating values account for its utilisation for power generation across the globe [3]. Therefore, coal is an integral part of the global energy mix and accounts for over 38-41% of the entire electric power generated yearly [4].

The utilization of coal for global electricity generation has catalysed rapid socio-economic growth, infrastructural development, and poverty alleviation [5-7]. Hence, the discovery of numerous coal deposits particularly in developing countries such as Nigeria (Africa's largest economy and most populous nation) has rekindled interest in coal power generation. Numerous reports in the literature have highlighted the urgent need to address Nigeria's perennial power problems [5,8]. The energy crisis is characterised by frequent power cuts and load shedding due to low generation, ineffective distribution, and transmission [9-10]. However, the fundamental problems of stable power generation and sustained supply could be potentially addressed through coal utilization for power generation in Nigeria [11-13].

The utilization of coal for electric power generation requires comprehensive data and insights into its fuel properties, engineering economics and potential impacts on the environment. The physical, chemical and thermal properties of coals could also assist engineers, planners and other stakeholders in the planning and design stages of the power plant development. Furthermore, data on coal properties could provide insights into the pollutant emissions, waste generation profile, and toxicity analyses during the power plant operations. However, the comprehensive data on various ranks of Nigerian coals are limited to the geological, geochemical, petrographic, petrologic, sedimentology, and mineralogical properties as reported in the literature [14-18].

Therefore, this paper seeks to characterise the fuel properties and energy recovery potential of Obomkpa (BMK), a newly discovered coal sample from Aniocha-North Local Government Area of Delta State in Nigeria. Consequently, the physicochemical, calorific, and thermal properties of BMK were characterised by selected ASTM standards and equipment.

2. Experimental

2.1. Physicochemical analysis

The physicochemical properties of BMK were deduced by ultimate, proximate, and calorific analyses. Firstly, the pulverised BMK of particle size < 250 μm was examined through an elemental analyser (Vario MACRO Cube, Germany) to determine its carbon (C), hydrogen (H), nitrogen (N), and sulphur (S) compositions based on the ASTM standard D5373. The proximate analysis was deduced by thermogravimetric analysis (TGA) as described in the literature [19]. The moisture (MC) was deduced at 110°C, whereas volatile matter (VM) was at 900°C under nitrogen (N_2) atmosphere. However, the ash content (AC) was determined at 900°C in air. Lastly, the fixed carbon (FC) was computed from the percentage difference between the sum of MC, VM and AC. The calorific value was determined by bomb calorimetry using the isoperibol bomb calorimeter (IKA C200, USA). Each test was carried out in duplicate to ensure the reliability and accuracy of the measurements presented as averaged values in Table 1.

2.2. Thermal analysis

Thermogravimetric analysis (TGA) was employed to examine the thermal degradation behaviour and energy recovery potential of BMK. For each TG experiment, 17-20 mg of BMK was weighed in an alumina crucible before placing in the TGA (Shimadzu TG-50, Japan). Next, the sample was heated under non-isothermal mode from 25°C to 900°C based on the flash heating rate of 50°C/min. For the flash oxidative (combustion) conditions, the sample was heated under air atmosphere (flow rate = 20 mL/min), whereas the flash non-oxidative (pyrolysis) process was performed under nitrogen (N_2) (flow rate = 20 mL/min). On completion, the TGA data were analysed using the in-built thermal analysis software (Shimadzu Workstation TA-60WS, Japan). Consequently, the resulting mass loss and derivative mass loss data were recovered and plotted against temperature to acquire the TG, DTG and conversion plots shown in Figures 1-3.

2.3. Temperature profile analysis

The thermal degradation of BMK was further examined by temperature profile analysis. Therefore, the temperature profile characteristics (TPC) were deduced for the thermal degradation of BMK under oxidative (combustion) and non-oxidative (pyrolysis) TG conditions. For this study, the TPCs deduced from the TA-60WS software were; the onset or ignition temperature (T_{ons}), midpoint temperature (T_{mid}), burnout or offset temperature (T_{off}), mass loss (M_L, %) and residual mass (R_M, %) from the TG plots in Figure 1. However, the drying and devolatilization peak temperatures were deduced from the DTG plots in Figure 3. Based on the TPCs, the thermal degradation behaviour of BMK was examined. This approach has been successfully employed by numerous researchers to describe the distinct degradation characteristics of thermally decomposing materials [20-21].

3. Results and discussion

3.1. Physicochemical properties

The ultimate, proximate, and calorific fuel properties of BMK in as-received basis (*a.r*) are presented in Table 1 on a comparative basis with a similar ranked coal in the literature [14].

Table 1. Physicochemical fuel properties of BMK

Elements/fuel property	Symbol/ units	Obomkpa (BMK) coal	Ogwashi-Asaba coal
Carbon	C (wt.%)	50.47	64.30
Hydrogen	H (wt.%)	5.66	6.50
Nitrogen	N (wt.%)	0.58	1.10
Sulphur	S (wt.%)	0.99	4.30
Oxygen	O (wt.%)	42.30	23.70
Moisture	MC (wt.%)	3.80	38.00
Volatile matter	VM (wt.%)	53.40	55.70
Fixed carbon	FC (wt.%)	26.47	29.70
Ash	AC (wt.%)	16.38	5.60
Higher heating value	HHV (MJ/kg)	19.66	16.50

Based on the findings, BMK contains C, H, N, S, O and MC, VM, AC, and FC as typically found in petroleum coke, biomass, and other coals [22-23]. In addition, BMK contains high C, H, O but low compositions of N and S. Calorific analysis showed that the higher heating value (HHV) of BMK is 19.66 MJ/kg, which classifies it as a Lignite A or Sub-bituminous C ranked coal [3]. Similarly, Ogala *et al.*, [14] examined the petrographic, mineralogical and geochemical properties of lignites from Ogwashi–Asaba in the Delta state of Nigeria. The findings showed that the compositions of C, H, N, and S are comparatively higher than BMK examined in this study.

The marked differences observed could be due to the level of coalification, origins, sampling, treatment or preparation methods of the coals, despite their similar rank and classification. Conversely, the proximate properties VM and FC of BMK were found to be in fairly good agreement with Ogala *et al.*, [14], although the MC and AC were markedly dissimilar. The AC was found to be in good agreement with raw lignite investigated by Agraniotis *et al.*, [24]. In general, the observations of BMK and the literature findings indicate that the mode of sampling, preparation and pre-treatment can influence the proximate fuel properties. Lastly, the HHV of BMK is in fairly good agreement with other lignites reported in the literature [24-25].

3.2. Thermal properties

The thermochemical analysis and energy recovery potential of BMK was investigated by thermogravimetric analysis (TGA). The resulting TG, conversion, and DTG plots for the oxidative (combustion) and non-oxidative (pyrolysis) processes are shown in Figures 1-3.

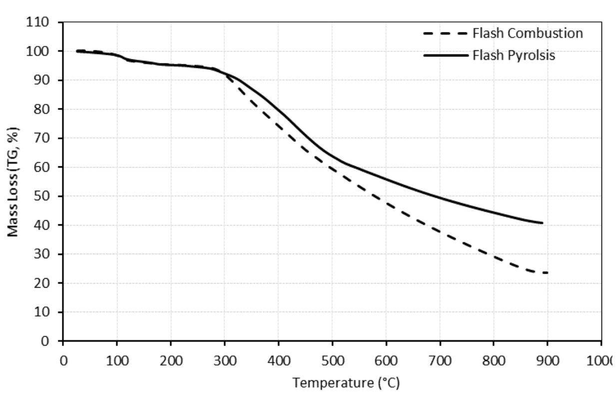

Figure 1. TG plots for flash conversions of BMK

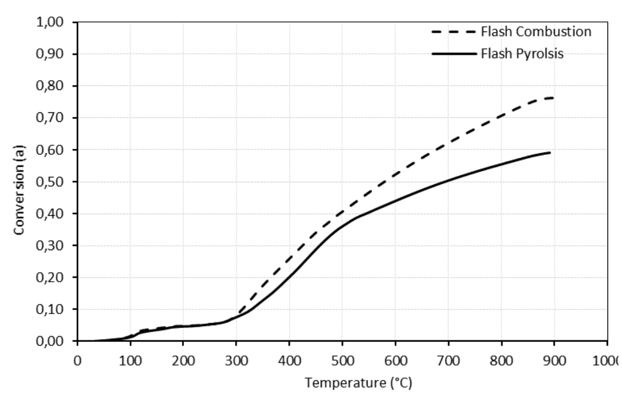

Figure 2. Conversion plots for flash conversions of BMK

The TG plots indicate BMK coal experienced significant mass loss as evident in the downward sloping plots which can be seen from left to right of Figure 1. The findings also indicate the increase in temperature resulted in significant thermal degradation of BMK. Consequently, the rate of conversion (Figure 2) increased with increasing temperature irrespective of the oxidising environment in which the process occurred. Typically, the thermal degradation of coal is ascribed to the breakdown of the organic matter or macerals (namely; inertinite, vitrinite and liptinite) in its structure [26]. During the process, the inertinite fraction first degrades at temperatures below 400°C, whereas the vitrinite fraction which accounts for the largest thermally degraded component occurs between 450°C and 600°C [27-28].

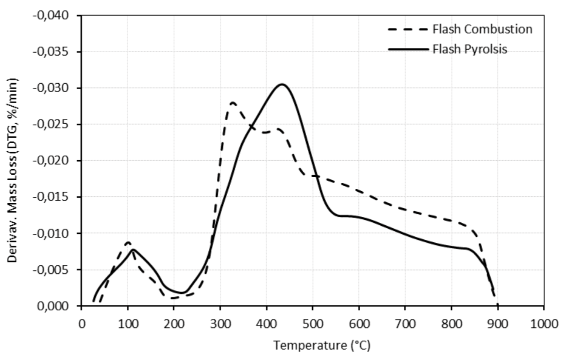

Figure 3. DTG plots for flash conversions of BMK Coal

The thermal degradation pathway for BMK was also examined through the DTG plots presented in Figure 3.

As observed, the thermal degradation of BMK resulted in various peaks indicating various reactions or processes occurred under both oxidative and non-oxidative TG conditions. The first set of peaks can be observed in the temperature range from 30°C to 200°C corresponding to mass losses of 4.72% and 4.76% for the oxidative (combustion) and non-oxidative (pyrolysis) processes, respectively. The mass loss observed during the thermal degradation processes is in good agreement with the moisture content (3.80%). This finding indicates loss of mass could be attributed to drying or the removal of surface moisture in BMK. However, the second set of peaks were observed from 200°C to 475°C for the oxidative (combustion), which consists of two peaks with maximum values observed at 326.58°C and 425°C. For the non-oxidative (pyrolysis) process, the single peak occurred between 200°C and 550°C. In comparison, the peaks in the second stage for the oxidative (combustion) process were observably smaller in size and slightly symmetric relative to the non-oxidative process, which confirms the exothermic and endothermic nature of the degradation processes, respectively.

3.3. Temperature profile characteristics

The effects of the oxidative (combustion) and non-oxidative (pyrolysis) conditions on the thermal degradation of BMK were examined by temperature profile characteristic (TPC). Tables 2 and 3 present the TPCs of BMK deduced from the TG and DTG plots, respectively. As observed, the BMK degradation process under oxidative (combustion) conditions resulted in higher mass loss of 76.56% compared to 59.27% for the non-oxidative process. This could be ascribed to the exothermic nature of the oxidative process, as earlier reported, which provides higher thermal energy required to degrade the coal maceral components compared to the non-oxidative process. Furthermore, the high mass loss could be ascribed to the higher temperature differences observed between the onset and burnout temperatures during the processes. For the oxidative process, the T_{ons} and T_{off} occurred between 260.47°C and 647.30°C indicating a temperature range of 386.83°C compared to 306.32°C for the non-oxidative process with T_{ons} and T_{off} of 295.16°C and 601.48°C, respectively.

Table 2. TG–TPCs for BMK thermal degradation under oxidative and non-oxidative conditions

Process	Onset temp. (°C)	Midpoint temp. (°C)	Offset temp. (°C)	Mass loss (%)	Residual mass (%)
Combustion	260.47	478.26	647.30	76.56	23.44
Pyrolysis	295.16	438.81	601.48	59.27	40.73

Consequently, the residual mass for the non-oxidative process was higher than the oxidative process. Typically, the oxidising environment and the residual mass of the processes is an indicator of the nature of the final products after thermal degradation. For oxidative (combustion) processes, the resulting mass of residuals is largely due to ash [29-30]. However, since the ash content for BMK is 16.38% (Table 1), it can be reasonably surmised that the residual mass from the oxidative TG process could also be due in part to coke (7.06%), ash and mineral matter. On the other hand, the residual mass of the non-oxidative process may be largely due to coke (24.35%) along with ash/ mineral matter. However, extensive coke or carbonization tests are required to empirically confirm the outlined submissions.

The TPCs for the DTG plots were also examined as presented in Table 3. As observed, the thermal degradation processes could be described in terms of drying, devolatilization, and coke degradation/ash formation depending on the oxidising nature of the process.

Table 3. DTG–TPCs for BMK thermal degradation under oxidative and non-oxidative conditions

Thermal process	Drying peak temperature (°C)	Peak drying rate (%/min)	Peak devolatilization temperature (°C)	Peak devolatilization rate (%/min)
Combustion	101.17	2.91	326.58	7.60
Pyrolysis	112.63	1.84	434.30	6.48

The results indicate that the peaks for the drying and devolatilization of BMK during the oxidative (combustion) process occurred at lower temperatures compared to the non-oxidative (pyrolysis) process. As earlier surmised, these observations could be ascribed to the higher energy input and exothermic nature of the combustion process, which ensured a higher rate of thermal degradation of BMK coal components. This view is also corroborated by the higher peak drying (2.91%/min) and devolatilization (7.60 %/min) rates observed during the oxidative (combustion) process compared to the non-oxidative process.

Overall, the findings indicate that the oxidative (combustion) process is more thermally efficient and could be utilised for future energy recovery or thermal energy applications. However, the non-oxidative (pyrolysis) process could also be beneficial for coke or carbon materials production used in various applications such as steel, iron ore or cement production. However, further tests are required to examine the properties of BMK for the proposed applications outlined in these preliminary studies.

4. Conclusion

The fuel properties and energy recovery potential of Obomkpa (BMK) coal from Delta State in Nigeria were examined and presented in this study. The ultimate, proximate, and calorific values showed that BMK contains high carbon, oxygen, volatile matter, fixed carbon, ash, and higher heating value. Comparison with other similar ranked coals revealed that BMK may either be lignite or subbituminous ranked coal. Thermal properties indicated the oxidative (combustion) process is a more thermally efficient compared to the non-oxidative (pyrolysis) process. However, further tests are required to examine the fuel properties and potential applications of BMK for electric power and materials applications.

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