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Fuel Characterization and Thermal Degradation Behaviour of Owukpa Coal

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Abstract

Coal is a fossil fuel and feedstock utilised globally for the production of chemicals, fertilisers and electricity. Intrinsically, coal is an integral part of the global energy mix and has significantly contributed to the socioeconomic growth and development of nations worldwide. With the second largest deposits in Africa, Nigeria is expected to invest in coal electricity in the future. However, limited data on the fuel characteristics, thermal degradation behaviour, and evolved pollutants profiles of Nigerian coals has hampered the establishment of coal power plants. Therefore, this study examined the physicochemical, mineralogical, and thermal properties of Owukpa (WKP) coal. The results showed that WKP contains high carbon, hydrogen, volatile matter, fixed carbon, ash and higher heating value but low nitrogen, sulphur, oxygen, and moisture. The mineral content was comprised of organic and inorganic mineral elements. The thermal analysis revealed significant mass loss (but low residual mass) for flash combustion (FCO) compared to low mass loss (high residual mass) for flash pyrolysis (FPY). The thermal decomposition of WKP under FCO and FPY occurred in two stages due to drying and devolatilization, although FCO was more thermally efficient than FPY. Consequently, WKP can be effectively utilised for energy recovery under either oxidative or non-oxidative conditions.

Keywords*: Fuel Characterization; Thermal Degradation; Owukpa, Benue; Nigeria.*

1. Introduction

Coal is an important fossil-based fuel and feedstock globally utilised for the production of chemicals, fertilisers and most importantly, electricity. As a result, coal remains an integral part of the global energy mix accounting for over 38% of global electricity generation [1]. Given its importance, analysts posit that coal will remain a crucial contributor to energy production and supply in the future. Accordingly, coal utilisation for energy production is expected to expand significantly in developing countries particularly India, China, and South Africa which have large deposits [2].

Likewise, the trend is expected to grow in Nigeria, which has the second largest deposits of coal in Africa [3]. Currently, it is estimated that Nigeria has 640 million tonnes of proven reserves along with 2.8 billion tonnes of inferred reserves. The distribution of Nigerian coal is comprised of 12% lignites, 49% subbituminous, and 39% bituminous [3]. Despite its huge potential, coal utilisation for electricity production in Nigeria remains insignificant [4]. As a result, Nigeria continues to experience severe power shortages resulting in an energy crisis that has stifled socio-economic growth and sustainable development.

The nation's inability to harness coal energy is attributed to numerous challenges which can be broadly categorised as socio-economic, environmental, and technological. Furthermore, the non-existence of coal in Nigeria's energy mix is due to the lack of comprehensive physicochemical, thermo-kinetic, and thermodynamic data on various Nigerian coals [5]. Current data on Nigerian coals is limited to its rheological [6], petrographic [7-8], geochemistry [9-10], and mineralogical [11-12] properties. Other studies have attempted to examine the power generation characteristics of selected coals in Nigeria [13-15].

However, there is limited data on the fuel characteristics, thermal degradation behaviour, evolved gas and pollutants profile of Nigerian coals along with its solid waste profiles after combustion. As a result, the design, operation, and maintenance of coal power plants in Nigeria remains plagued by such technical issues. Therefore, it is important to critically examine the fuel properties of various Nigerian coals such as Owukpa, which is a sub-bituminous coal from Benue state in Nigeria. Aptly termed the "food basket of the nation", Benue state produces large quantities of fresh agricultural produce annually. However, the lack of power supply has hampered the efficient storage, transportation, and conversion of the farm produce into finished products, thereby resulting in huge economic losses, waste disposal, and environmental challenges.

Therefore, the main objective of this study is to examine the fuel characteristics and thermal properties of Owukpa coal as a potential feedstock for future power generation in Nigeria. The study presents the physicochemical, microstructural, mineralogical and thermal properties of Owukpa (WKP) coal. It is envisaged that the findings will avail engineers, policy, and decision makers with comprehensive data on Owukpa coal required to implement technologically, economical and environmentally friendly strategies for future energy recovery in power plants.

2. Experimental

The Owukpa coal sample was supplied by Ehinehi Nigeria Enterprises Limited – a mining and prospecting company based in the Federal Capital Territory, Abuja, Nigeria. The rock sample was crushed, ground, and sieved to obtain homogeneous sized particles below 250 μm. Next, the powdered Owukpa (WKP) was subjected to physicochemical analysis in which the sample was characterised by ultimate, proximate, and calorific analyses to examine its elemental, proximate and higher heating values (HHV). The elemental analysis was performed on the CHNS elemental analyser (Model: vario MACRO Cube, Germany) based on ASTM standard D5373-93.

The proximate analysis was performed by thermogravimetric analysis (TGA) based on the procedure described in the literature [16]. The higher heating value was determined by combustion calorimetry using an oxygen bomb calorimeter (Model: IKA C2000, USA) based on the isoperibolic measurement procedure described in ASTM standard D2015. The surface morphology, microstructure, and mineral composition of WKP were examined through Scanning Electron Microscopy (SEM). The SEM was fitted with an Energy Dispersive X-ray (EDX) detector (Model: JEOL-JSM IT 300 LV, Germany) and analysed based on procedures previously described in the literature [17].

Lastly, the thermal analysis of WKP was performed to examine its degradation behaviour and characteristic profile temperatures (TPC) under flash combustion and pyrolysis conditions. The non-isothermal thermogravimetric analysis (TGA) was performed by heating 10 mg of pulverised WKP in an alumina crucible at a heating rate of 50°C/min from room temperature (RT) to 900°C. For flash pyrolysis, ultra-pure nitrogen (flow rate 20 mL/min) was employed to flush the TG analyser whereas air (flow rate of 20 mL/min) was employed for flash combustion. The objective was to examine the thermal properties of WKP under conditions similar to pulverised coal combustion and pyrolysis. On completion, the raw data was retrieved and plotted as mass loss (TG, %) and derivative mass loss (DTG %/min) against temperature in degrees Celsius. Next, the temperature profile characteristics (TPC) of WKP were determined through the Shimadzu thermal analysis software (version: TA-50 Workstation) to examine its thermal degradation behaviour (TDB). The TPCs examined in this study were; onset or ignition (T_{on}), midpoint (T_{mid}), and maximum decomposition (T_{max}), and burnout (T_{off}) temperatures together with the mass loss (M_L, %) and residual mass (R_M, %) of WKP coal. The definition of the TPC terms is detailed in our previous study [17].

3. Results and discussion

3.1. Physicochemical analyses

The physicochemical properties of Owukpa (WKP) coal was examined by ultimate, proximate, calorific analysis and the results presented in Table 1. The results were compared with the values of Owukpa reported in Chukwu *et al.,* [3].

Table 1. Physicochemical properties of Owukpa coal

Analysis	Element	Symbol (Unit)	This Study	Chukwu *et al.,* [3]
Ultimate	Carbon	C (wt.%)	65.40	67.82
	Hydrogen	H (wt.%)	5.23	5.88
	Nitrogen	N (wt.%)	1.60	1.43
	Sulphur	S (wt.%)	0.46	0.60
	Oxygen	O (wt.%)	27.32	9.47
Proximate	Moisture	MC (wt.%)	6.50	11.50
	Volatile matter	VM (wt.%)	31.49	39.10
	Fixed Carbon	FC (wt.%)	41.78	46.10
	Ash	AC (wt.%)	20.23	3.30
Calorific	Heating Value	HHV (MJ/kg)	26.67	26.51

The results in Table 1 indicate the elemental composition of WKP consists of high proportions of C and H but low N, S, and O content. The proximate composition of WKP indicates high volatiles (VM), fixed carbon (FC) and ash (AC) but low moisture (M) content. The calorific value was 26.68 MJ/kg, which according to ASTM D388 standard [18] categorises WKP as a subbituminous A, non-agglomerating low-rank coal (LRC). Furthermore, the HHV of WKP is significantly higher than other Nigerian coals from Garin Maiganga (23.74 MJ/kg) [19], Inyi (19.39 MJ/kg), and Ezimo (20.96 MJ/kg) [3], Ihioma (20.33 MJ/kg) and Ogboligbo (16.33 MJ/kg) [20]. However, it is in good agreement with the HHV of 26.51 MJ/kg reported for Owukpa in Chukwu *et al.,* [3]. In addition, the CHNS and proximate (MC, VM, FC) properties of WKP in this study are in fairly good agreement with Chukwu *et al.,* [3]. However, there are striking differences of 17.85 wt.% and 16.93 wt.% in the oxygen (O) and ash (A) content, respectively. This observation may be due to the methods of coal sampling, preparation, and characterisation techniques employed in both studies.

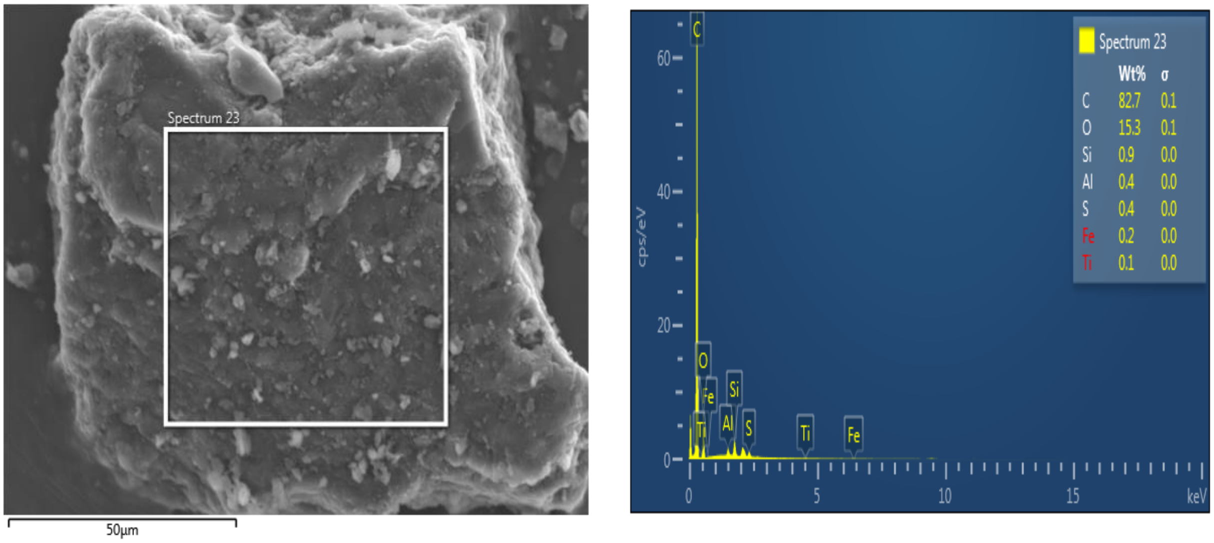
3.2. Microstructure and mineralogical analyses

The SEM micrographs for Owukpa coal are presented in Figures 1 (a) and (b). As observed in Figure 1 (a), the micrograph reveals Owukpa coal consists of a heterogeneous mix of fine and coarse-grained particles characterised by a distinctive glossy appearance. This is due to the composition of metallic elements present in the complex structure of the coal. Therefore, the mineralogical composition of WKP was examined through Energy Dispersive X-ray (EDX) to determine its constituents. The EDX is presented in the electron micrograph in Figure 1(b).

As observed in Figure 1(a), the mineralogical composition of WKP is due to the elements C, O, Si, Al, S, Fe, and Ti (wt.%) in decreasing order of magnitude. The composition of each element in the WKP structure is presented in weight per cent (wt.%) in Table 2.

Table 2. Mineral composition of Owukpa coal

Coal element	Chemical symbol	Composition (wt.%)	Coal element	Chemical symbol	Composition (wt.%)
Carbon	C	82.74	Sulphur	S	0.40
Oxygen	O	15.29	Iron	Fe	0.18
Silicon	Si	0.90	Titanium	Ti	0.06
Aluminium	Al	0.43			



(a) (b)

Figure 1. SEM/EDX micrographs for Owukpa coal

As observed in Table 2, the mineral composition of WKP is mainly carbon (C=82.7 wt.%), oxygen (O=15.3 wt.%), silicon (Si=0.90 wt.%) and aluminium (Al=0.43 wt.%) with trace amounts of iron (Fe=0.18 wt.%) and titanium (Ti=0.06 wt.%). The elements of silicon and aluminium indicate the presence of oxides of silicon (SiO_2), aluminium (Al_2O_3), sulphur (SO_3), iron (Fe_2O_3), and titanium (TiO_2). In addition, the mineral composition may also contain silicates, sulphates, sulphides, and carbonate compounds.

In summary, the EDX results indicate that WKP coal has high mineral matter which may account for the high ash content reported in Table 1. The potential energy recovery from WKP particularly under oxidative conditions will potentially result in the deposition of high ash content rich in mineral matter. This could cause ash deposition and eventual operational challenges due to fouling, sintering, and agglomeration in equipment during coal conversion in power plants. Therefore, further tests are required to critically examine the ash and mineral matter content of WKP and its effects on thermal conversion.

3.3. Thermal analyses

The TG-DTG plots for the flash combustion (FCO) and flash pyrolysis (FPY) for Owukpa (WKP) are presented in Figures 2 and 3.

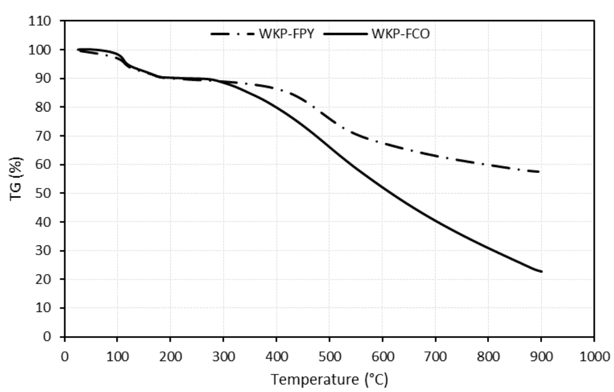


Figure 2. TG plots for flash combustion and pyrolysis of WKP

As observed in Figure 2, the thermal analysis of WKP under flash combustion and pyrolysis resulted in a progressive mass loss (M_L) and ultimately a mass of residues (R_M). The FCO process resulted in a more significant M_L as evident in the curved plot in Figure 2. This may be due to the oxidative nature of the process resulting in the exothermic reactions that ensured significant thermal degradation of WKP coal constituents. However, the thermal degradation of WKP under FPY resulted in lower M_L due to the non-oxidative and endothermic nature of the process.

As a result of the difference in operating conditions, it is expected that thermal degradation behaviour, thermal reactivity, and temperature profile characteristics (TPC) of WKP will vary distinctly. To examine the thermal degradation behaviour, the TPCs were deduced from the Shimadzu Thermal analysis software (version: TA-50 Workstation). The results of the TPCs deduced from the TG plots are presented in Table 3.

Table 3. TG-TPCS for Flash Pyrolysis and Combustion of Owukpa coal

Thermal analysis	Onset temperature (T_{ons}, °C)	Midpoint temperature (T_{mid}, °C)	Offset temperature (T_{off}, °C)	Mass loss (M_L, %)	Residual mass (R_M, %)
FPY	339.06	469.41	617.25	42.09	57.91
FCO	274.56	519.47	759.23	77.41	22.59

As can be observed in Table 3, the thermal degradation of WKP under FPY (flash pyrolysis) resulted in 42.1% mass loss (M_L) compared to 77.4% during FCO (flash combustion). As a result, the residual mass (R_M) for FPY and FCO were 57.9% and 22.6%, respectively. Based on the onset (T_{ons}) and offset (T_{off}) TG-TPC temperatures, the FPY occurred between 339.06°C and 617.25°C whereas the FCO occurred between 274.56°C and 759.23°C. This indicates that FCO occurred over the temperature range of 484.67°C compared to 278.19°C for FPY accounting for the higher M_L (and lower R_M) in the former compared to the latter.

Next, the thermal degradation behaviour and decomposition pathway for the FPY and FCO of WKP coal were also examined by derivative thermogravimetric analysis (DTG). The DTG plots are presented in Figure 3.

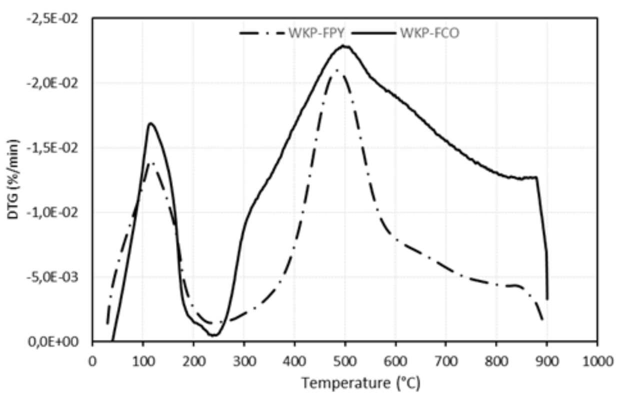


Figure 3. DTG plots for flash combustion and pyrolysis of WKP

As observed in Figure 3, the DTG plots for FPY and FCO are characterised by two predominant set of peaks in two distinct regions. The first region occurred between RT and 250°C whereas the second region was from 250°C to 900°C. Since the first region occurred below 250°C thereby resulting in mass loss below 10%, it can be ascribed to loss of moisture or drying of WKP during FPY and FCO. However, the mass loss in the second region was significantly higher than during drying and ascribed to the loss of volatile matter (or devolatilization) in WKP. The degree or rate of mass loss and the TPCs for drying and devolatilization were examined as presented in Table 4.

Table 4 DTG-TPCS for Flash Pyrolysis and Combustion of Owukpa coal

Thermal Analysis	Peak drying temperature (D_{max}, °C)	M_L rate (%/Min)	Peak devolatilization temperature (T_{max}, °C)	M_L Rate (%/Min)
FPY	116.48	3.86	487.41	5.53
FCO	116.17	5.50	495.84	5.26

As observed in Table 4, the D_{max} (peak drying temperature) for FPY and FCO differ slightly during drying. Furthermore, the rate of M_L at D_{max} for FPY (3.9 %/min) is lower than that for FCO (5.5 %/min). Similarly, the devolatilization peak temperature (T_{max}) for FPY and FCO differed slightly during devolatilization. This indicates that the oxidative or non-oxidative nature of the process does not significantly influence the M_L rate or degradation pathways during the FPY and FCO of WKP under the conditions examined in this study.

4. Conclusion

The paper examined the fuel characteristics and thermal degradation of Owukpa (WKP) coal from Benue state in Nigeria. The fuel characteristics of WKP were examined based on elemental, proximate, and calorific analyses. On the other hand, the thermal degradation behaviour was examined by non-isothermal thermogravimetric analysis under flash combustion (FCO) and flash pyrolysis (FPY) conditions. The results indicate Owukpa coal contains high proportions of combustible elements (C, H) but low pollutant elements (N, S) and O. The proximate properties revealed low moisture content but significantly high proportions of volatile matter, fixed carbon, ash and higher heating value. The mineralogical composition of WKP is due to C, O, Si, Al, S, Fe, and Ti elements in decreasing order. The thermal degradation of WKP revealed significant mass loss (but low residual mass, R_M) for flash combustion (FCO) whereas the pyrolysis process (FPY) was characterised by low mass loss (but high residual mass, R_M). This demonstrates that the FCO process is more thermally efficient compared to FPY. The DTG plots revealed WKP decomposes in two stages characterised by drying and devolatilization. Lastly, the TPCs indicated that the degradation pathways for FCO and FPY are similar as observed in the study. In general, the fuel characteristics and thermal properties of WKP confirmed it is a prospective fuel for energy recovery under either oxidative or non-oxidative conditions provided the high ash content can be addressed.

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