PHYSICOCHEMICAL CHARACTERIZATION AND THERMAL DECOMPOSITION OF GARIN MAIGANGA COAL

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Abstract

The paper examined physicochemical and thermal characteristics of the newly discovered Garin Maiganga (GMG) coal from Nigeria. The physicochemical characterization comprised of elemental, proximate, calorific value, and classification (rank) analyses. Thermal analysis was examined using combined Thermogravimetric (TG) and Derivative Thermogravimetric analyses (DTG). Hence, the coal was heated from 30°C to 1000°C at 20°C/min under inert conditions to examine its thermal degradation behaviour and temperature profile characteristics (TPC). The results indicated that the GMG coal fuel properties consist of low Ash, Nitrogen, and Sulphur content. Moisture content was > 5%, Volatile Matter > 50%, Fixed Carbon > 22%, and Heating Value (HHV) 23.74 MJ/kg. Based on its fuel properties, the GMG coal can be classified as a Sub-Bituminous B, non-agglomerating low rank coal (LRC). The GMG coal TPCs – onset, peak, and offset temperatures – were 382.70°C, 454.60°C, and 527.80°C, respectively. The DTG profile revealed four (4) endothermic peaks corresponding to loss of moisture (drying), volatile matter (devolatization), and coke formation. The residual mass R_m was 50.16%, which indicates that higher temperatures above 1000°C are required for the complete pyrolytic decomposition of the GMG coal. In conclusion, the results indicate that the GMG coal is potentially suitable for future utilization in electric power generation and the manufacture of cement and steel.

Key words: Nigerian Coal, Thermal Decomposition, Garin Maiganga, Pyrolysis, Nigeria.

1 INTRODUCTION

Coal is the most affordable and widely distributed fossil fuel in the world [1]. With demand set to soar by 2.6%, the influence of coal as feedstock for energy and industry will remain significant, potentially accounting for 14.5% of global energy mix by the year 2035 [2]. Currently, coal accounts for about 40% of global electric power generation despite concerns about CO_2, greenhouse gas (GHG) emissions, and the long term sustainability of the planet [3]. With the ratification of the Paris Agreement in 2015, global leaders pledged to curtail climate change and limit global warming to 2°C by divesting from polluting fossil fuels and supporting renewables [4]. However, the total elimination of fossil fuels like coal from the global energy mix in favour of clean renewable energy is plagued by numerous challenges. Potential solutions will require comprehensive understanding of the socioeconomic, environmental, and technological dynamics of fossil to clean energy transitions [5]. Even so, coal presents a unique opportunity for cheap, abundant energy through clean conversion technologies (CCT) [6]. Typically, CCTs are aimed at reducing carbon emissions and other harmful gaseous pollutants generated from burning coal in power plants. The most notable examples of CCT include Advanced Coal Pyrolysis (ACP), Supercritical or Ultra-critical Coal Gasification (S-UCG), and Integrated Gasification Combined Cycle (IGCC) with Carbon Capture and Storage (CCS) [7]. The use of CCTs reportedly improves power plant operating conditions resulting in higher thermal efficiencies, low waste and pollutant gaseous emissions [8-10].

Furthermore, the generation of electric power from CCTs has the potential to significantly impact the socioeconomic growth, sustainable development, and environmental protection in developing economies like Nigeria with its huge coal deposits. Nigeria's coal reserves are estimated to be around 2 billion metric tons [11], with over 650 million metric tons of economically recoverable resources [12]. In addition, the discovery of new deposits in Shankodi-Jangwa, Afuze, and Garin Maiganga has revitalized the prospects of coal power generation in Nigeria.

Conversely, efforts at utilizing Nigerian coals for various applications are hampered by a lack of comprehensive scientific data on their characteristic properties [13]. The composition of coals depend on factors such as coalification process, diagenesis, depositional surroundings, and hydrological settings [14]. However, there is limited research on the physico-chemical, thermal, and kinetic fuel properties of Nigerian coals, as most reports are focused on rheological, petrological, mineralogical, and geological properties [15-18]. In addition, a lack of fuel property data for newly discovered Nigerian coals such as the GMG coal significantly limits their potential applications. This is because the fuel property data is vital for the engineering design, techno-economic analysis, and optimization processes for coal conversion. Furthermore, such fuel characterization is an essential prerequisite for assessing the coal rank and classification required for its efficient utilization as a potential feedstock for conversion. However, there is limited research on the characterization of the GMG coal, its fuel property and potential future applications. Coal characterization is generally accomplished by Ultimate/Proximate analyses, Bomb Calorimetry, Combined Thermogravimetric (TG) and Derivative Thermogravimetric (DTG) analysis, Differential Scanning Calorimetry (DSC), and Fourier Transform Infra-Red (FTIR) spectroscopy [19].

The main objective of this study is to characterize, classify, and compile comprehensive scientific data on the physicochemical and thermal characteristics of the Garin Maiganga (GMG) coal recently discovered in Nigeria. The physicochemical characterization will consist of ultimate analysis, proximate analysis, calorific value, and its application in the rank classification of the GMG coal. Based on the thermal properties, the thermal degradation behaviour and temperature profile characteristics (TPC) of the GMG coal will be examined.

2 EXPERIMENTAL

The coal sample was acquired from the Garin Maiganga coalfield in the Akko Local Government Area of Gombe State in Nigeria. The coal was pulverized and sifted using a laboratory sieve to obtain 250μm sized particles prior to characterization. Consequently, its elemental composition was determined using a CHNS analyzer (model: El vario MICRO cube) according to the ASTM standard D5291. Next, a proximate analysis was examined according to ASTM D3173-75. The oxygen and fixed carbon contents were determined by difference.

The calorific value was determined using the IKA C2000 bomb calorimeter according to the ASTM D2015 test method for the higher heating value (HHV). The mineral matter was calculated using the *Parr* equation ($Mm = 1.08A + 0.55S$), where A - ash; and S - sulphur content [20]. All measurements were carried out in triplicate.

The thermal decomposition behaviour of the GMG coal was examined through combined Thermogravimetric (TG) and Derivative Thermogravimetry (DTG) using the *Netzsch* 209 F3 Tarsus^{TM} thermal analyzer. For each run, 9.3 mg of the GMG coal was placed in an alumina crucible and heated from 30°C to 1000°C at 20 °C/min using nitrogen as purge gas. The resulting thermograms were subsequently analyzed using the *Netzsch* thermal analysis software (Proteus version 6.1) to deduce the weight loss (%), derivative weight loss (%/min), and the temperature profile characteristics (TPC). The TPCs are the temperature characteristics used to examine the thermal decomposition behaviour of materials. The TPCs include: onset temperature, T_{on}, maximum peak decomposition temperature, T_{max}, and burnout temperature, T_{end}. The T_{on} is the temperature at which the pyrolytic decomposition (devolatilization) of the material begins. The T_{max} is the temperature at which the maximum decomposition (%/min or mg/min) of the material occurs as denoted by the largest peak observed in the DTG analysis. Lastly, T_{end} is the temperature that denotes the end of devolatilization during the thermal decomposition of the material.

3 RESULTS AND DISCUSSION

3.1 Chemical properties

The chemical properties of the GMG coal, comprising the elemental, proximate, heating value, and the mineral matter are presented in Table 1. The values have been compared with reported average values of coals in literature [21].

Tab. 1 Chemical Fuel Properties of GMG coal

Fuel Property	Symbol/Unit	GMG coal	Literature values [21]
Ultimate analysis			
Carbon	C	61.80	62.9 – 86.9
Hydrogen	H	4.43	3.5 – 6.3
Nitrogen	N	1.08	0.5 – 2.9
Sulphur	S	0.42	0.2 – 9.8
Oxygen	O	32.26	4.4 – 29.9
Proximate Analysis			
Moisture	M	5.30	0.4 – 20.2

Fuel Property	Symbol/Unit	GMG coal	Literature values [21]
Volatile Matter	*VM*	51.08	12.2 – 44.5
Ash	*A*	20.97	5.0 – 48.9
Fixed Carbon	*FC*	22.64	17.9 – 70.4
Higher Heating Value	*HHV (MJ/kg)*	23.74	16.0 – 34.0
Lower Heating value	*LHV (MJ/kg)*	22.79	-
Mineral Matter	*Mm*	22.88	-

The elemental composition of the GMG coal revealed high proportions of carbon, volatiles, ash, and fixed carbon but low proportions of moisture, nitrogen, and sulphur. In addition, the mineral matter content was higher than the ash content possibly indicating the abundance of metal oxides in the GMG coal. The presence of metals is known to increase the reactivity of coals [22].

The heating value of the GMG coal was 23.74 MJ/kg, which is significantly higher than the value of 20.86 MJ/kg previously reported by *Rhemshak* and *Jauro,* [13]. The observed difference may be due to the methods of measurement by the authors. Nevertheless, the value is within the range typically reported for coal samples but higher than that of other carbonaceous solid biofuels [23], agricultural waste (Oil Palm Empty Fruit Bunches – 17.57 MJ/kg) [24, 25], and energy grasses (Spear grass – 17.03 MJ/kg) [26].

Based on the ASTM standard D388-12, the ranking classification of the GMG coal was examined using its volatile matter (VM) and higher heating value (HHV) [27]. Consequently, the GMG coal is a Sub-Bituminous B, non-agglomerating, low rank coal (LRC). Therefore, the GMG coal can be utilized for iron, steel, or cement production, electric power generation, or co-firing with biomass [28].

3.2 Thermal properties

Figure 1 presents the TG-DTG plots for the thermal decomposition of the GMG coal under non-isothermal heating conditions. The TG curve displayed the downward sloping curve signifying the weight loss typically observed for carbonaceous materials [29, 30].

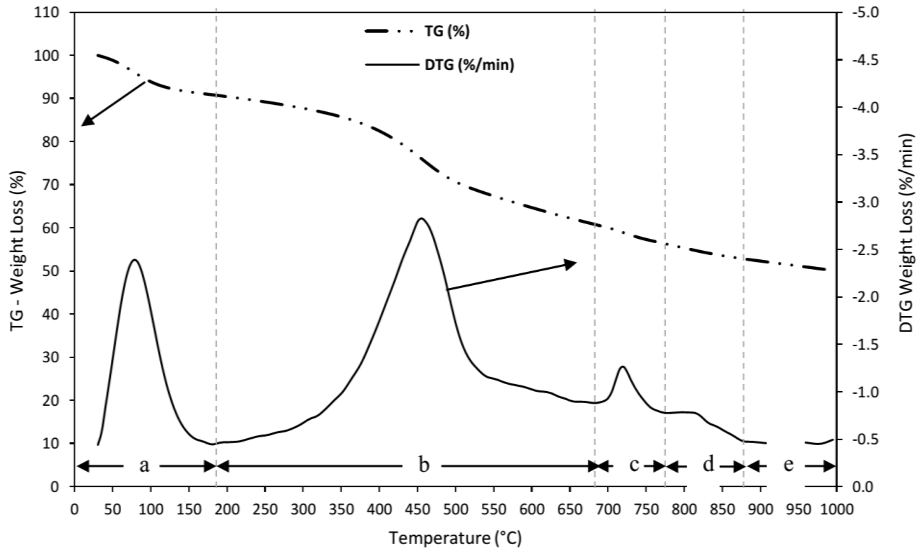

Fig. 1 TG-DTG plots for GMG coal

The DTG plots revealed four (4) endothermic peaks: 30–185 °C; 185–685 °C, 685–780 °C, and 780–885 °C. This suggests that the devolatization occurred in five (5) stages denoted as; *a, b, c, d,* and *e* in Figure 1. The observed results differ markedly from the thermal behaviour of other coals reported in literature [19]. This may be due to the high reactivity of the GMG coal based on its high ash (20.97%) and volatile matter (51.08%).

The first peak which occurred at 30–185 °C can be ascribed to drying, characterized by the loss of moisture and low molecular weight (LMW) volatile compounds. The total weight loss in this stage was 9.22%. The second peak from 185°C to 685 °C was characterized by a significant weight loss of 30.06%. The weight loss of materials at 200–600°C during TG pyrolysis is usually significant due to the loss or devolatization of volatile matter. The breakdown of coal within the temperature range of 185–685°C can therefore be ascribed to the loss of volatile matter. However, the difference in the actual weight loss during the devolatization of the GMG coal and the volatile matter of the GMG coal, presented in Table 1, may be due to incomplete pyrolysis.

Similarly, the weight loss from 685°C to 780°C and from 780°C to 885°C can be ascribed to the devolatilization of less reactive volatile matter in the coal structure. The total weight loss during these stages was 4.58% and 3.26%, respectively. Consequently, the total weight loss for the coal during the TG analysis from 30°C to 1000°C was 49.84%. Finally, the tailing observed from 885°C to 1000°C can be ascribed to char or coke formation observed during the pyrolytic decomposition of carbonaceous fuels [5].

3.3 Temperature Profile Characteristics

Table 2 presents the detailed temperature profile characteristics (TPC) of the GMG coal during the TG analysis.

Tab. 2 Temperature Profile Characteristics of GMG coal

Temperature Characteristic	Abbreviation	Unit	Value
Maximum Drying	*Dry* T_{max}	°C	78.50
MLR (%/min)	*MLR*	(%/min)	-2.39
Onset (Ignition) Temperature	T_{on}	°C	382.70
Maximum Devolatization Peak Temperature	T_{max}	°C	454.60
MLR (%/min)	*MLR*	(%/min)	-2.83
Burnout Temperature	T_{end}	°C	527.80
Residual mass	R_m	%	50.16
Mass of Coal decomposed	D_m	%	49.84

The TPC for the GMG coal are: onset temperature T_{on} = 382.70°C, maximum peak decomposition temperature T_{max} = 454.60°C, and burnout temperature T_{end} = 527.80°C. This indicates that the thermal decomposition of the GMG coal commences at 382.70°C which is significantly higher than the average ignition temperature of 256°C reported for other coals by *Vassilev et al.,* [21]. In contrast, the T_{max} = 454.60°C is observably lower than the values (470–580°C) for the pyrolysis of other Nigerian coals namely: Lamja, Chikila, Enugu, and Agbogugu [29].

Similarly, the burnout temperature T_{end} = 527.80°C is significantly lower than the range of values (730–780°C) reported for the coals. This indicates that the GMG coal is more reactive than the selected Nigerian coals with a higher potential for the release of volatile gases during pyrolysis. The residual mass R_m was 50.16%, indicating only 49.84% of the GMG coal was thermally decomposed under pyrolysis conditions. This indicates that higher temperatures above 1000°C are required for the complete conversion of the GMG coal through pyrolysis for future applications.

4 CONCLUSION

The physicochemical and thermal characteristics of the Garin Maiganga (GMG) coal were examined in this study. The results indicate that the GMG coal possesses high proportions of C, H, O, VM, FC, ash content but low ash, N, and S contents. Based on its heating value (HHV), it may be classified as a Sub-Bituminous B, non-agglomerating, and low rank coal (LRC). The thermal properties of the GMG coal revealed higher reactivity compared to other Sub-Bituminous Nigerian coals reported by other groups. The DTG profile revealed four (4) endothermic peaks during the pyrolytic decomposition from 30°C to 1000°C corresponding to the loss of moisture, volatile matter, and high residual mass, which may be ascribed to coke formation. This indicates that temperatures above 1000°C are required for the complete pyrolytic decomposition of the GMG coal. Therefore, the authors recommend that future studies on the GMG coal should be carried out at higher reaction temperatures and different heating rates using air or oxygen as the purge gas. This will increase the coal conversion efficiency and potential industrial applications of the GMG coal as obtainable in Pulverized Coal Combustion (PCC) for electric power generation and the production of cement, iron or steel.

ACKNOWLEDGMENT

The authors would like to acknowledge contributions of Dr T. A. T. Abdullah and Dr S. L. Wong of Universiti Teknologi Malaysia (UTM), and Faizal M. B. Halim of Universiti Teknologi Mara (UiTM) for assistance with the TG-DTG analysis.

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