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AN EVALUATION OF THE COKING CHARACTERISTICS OF POLISH COKING COALS FOR COKEMAKING WITH NON-COKING NIGERIAN COALS

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ABSTRACT

The proximate analysis and laboratory coking properties of Nigerian Enugu, Okaba, Lafia and Bellview coals A and B imported from Poland were determined. For the Nigerian coals, ash contents (db) of 7.89%, 8.80%., 25.99%, volatile matter (daf) of 54.63%, 64.69%, 31.00%, sulphur (db) of 0.44%., 0.70% 2.34% were determined for Enugu, Okaba and Lafia coals, respectively. For the Polish coals, ash contents (db) of 5.80%, 6.10%, volatile matter (daf) of 31.80%, 31.30%, sulphur (db) of 0.60%, 0.70% were analyzed for Bellview A and B, respectively. Furthermore, for Nigerian coals free swelling index (FSI) of 0,0,6 were determined for Enugu, Okaba and Lafia coals, respectively. For the Polish coals, FSI values of 2.5, 2.5, Gieseler maximum fluidity of 48 ddpm, 38 ddpm and G-coking capacity of 0.97, 0.93 were determined for Bellview A and B, respectively. The Nigerian Enugu and Okaba coals are thus non-caking sub-bituminous coals, while Lafia coal is a medium coking coal with intolerably high ash and sulphur contents. The Bellview coals are medium volatile coking coals of ISO codes 523 and 522, respectively. The relatively high G-value for Bellview A indicates that the coal may be self coking, but it may not accommodate the non-caking Enugu and Okaba coals and the high ash and high sulphur Lafia coals in blends for cokemaking. Blend calculations showed that up to 26.38% of the high ash, high sulphur Lafia coal can blend with 24.98% Bellview A and 48.64% prime coking UK Ogmore coal.

Keywords: Coal, Coking, Blends, G-value

1. INTRODUCTION

Coal are organic sedimentary rocks that have their origin from a variety of plant materials and tissues deposited in more or less aquatic locations [1]. Coals vary in rank depending on the degree of maturity they attained in the course of metamorphism. Unfortunately, the bituminous coking coals are scarce worldwide accounting for only about 5% of the world's supply of coals [2].

A coal is characterized by a number of chemical, physical, physico-chemical and petrographic properties. In proximate analysis, moisture, ash, volatile matter and fixed carbon are determined. When bituminous coals are heated, they develop plastic properties at about 350^{0}C and as a result exhibit fluidity, swelling, expansion and contraction in volume and after carbonization produce a coherent residue whose strength depend on the rank of the coal. This plastic property of coals is commonly indicated in free swelling index, Gieseler plastometry, Ruhr dilatometry and Gray-king assay tests [3,4].

Gieseler plastometer and Ruhr diatometer are commonly used to study coals' plastic properties for cokemaking. In Gieseler plastometry, the softening temperature, re-solidification temperature and maximum fluidity of coals are determined to predict their cokeability. In Ruhr dilatometry, the coking capacity, G, defined by Simonis as:

$$G= \frac{(E+V)}{2} * \frac{(c+d)}{V_*c+E_*d} \qquad (1)$$

is used to predict the cokeability of coals [5,6].

In pursuit of its plan to develop the integrated steel plant at Ajaokuta, the Federal Government of Nigeria was able to locate coal deposits at Enugu, Okaba and Lafia with proven reserves of 54,74 and 22 million tons, respectively. Of these three deposits, only Lafia coal is medium coking but with intolerably high ash and sulphur content of 25.60% and 2.30%, respectively [7]. In an attempt to source for prime coking coals that can produce cokeable blends with Nigerian coals, Bellview coking coals was imported from Poland. In this research work, Bellview coal samples were subjected to bench scale coal characterization tests and their potential to produce cokeable blends with Nigerian coals was evaluated. The current international market prices of about US$300 per ton for coking coal and the non-availability of a high grade local coking coal makes research in the area of blend co-carbonisation more urgent [8].

2. MATERIALS AND METHODS

MATERIALS

Samples of Nigerian coals from Enugu, Okaba and Lafia deposits and Polish coals imported by Bellview Nigeria Ltd.

METHODS

The laboratory coking tests conducted are proximate analysis, free swelling index, Gieseler plastometry, Ruhr dilatometry, and sulphur determination by classical Eschka method. For proximate analysis and Ruhr dilatometry the samples were pulverized to pass 250 microns, while for Gieseler plastometery it was pulverized to pass 425 microns.

Proximate Analysis [9]

Proximate Analysis involves determination for moisture, ash, volatile matter and fixed carbon.

Moisture Content

The silica crucible for the test was preheated at 105^{o}C for 1 hour. One gramme of coal sample was then placed in the crucible and heated at 105^{o}C for 1 hour. The loss in weight accounts for the moisture content.

Volatile matter

The standard crucible was preheated in the muffle furnace at 970^{o}C for 7 minutes. The crucible was cooled in the desiccators and 1 gramme of coal sample was placed in it with three drops of benzene. The crucible (with the lid on) was now placed in the muffle furnace at 970^{o}C for 7 minutes. The loss in weight accounts for the volatile content of the coal.

Ash

The standard silica crucible was preheated at 825^{0}C for 1 hour. It was then cooled in the desiccators. One gramme of coal sample was placed in the crucible (with the lid on) and it was heated at 825^{o}C for 1 hour. The incombustible residue gives the ash content of the coal.

Fixed carbon

The fixed carbon is obtained from the relation:

Fixed carbon% = 100 – Moisture % - Ash% - Volatile matter% (2)

The results of proximate analysis are presented in Table 1.

Free swelling index

One gramme of coal sample was heated in a silica crucible on Bunsen flame for 7 minutes. The coke button obtained was then compared with the standard profiles to determine crucible-swelling number. The result of the crucible swelling tests are presented in Table 2.

Gieseler Plastometry

Gieseler plastometry involves determination for the coal's softening temperature, resolidification temperature and maximum fluidity. 5g of the coal sample ground to pass 425 microns was compressed by a 10kg weight placed on the sample with the stirrer arms fully embedded. After assembling, the coal sample was heated as programmed on the Gieseler programmer. The stirrer was immobile at the start of the heating since the rabble arms were rigidly held by the compressing coal. The movement only started when the coal softened and continued as long as the coal remained in the plastic state. The movement stopped when the coal resolidified. The results obtained are presented in Table 2

Ruhr Dilatometry

The coal sample ground to pass 250 microns was compacted into a pencil form. The coal pencil was then placed in a metal tube and a piston rod was inserted into the tube to rest on the pencil top. The other end of the piston rod was attached to a rotating barrel to record the vertical movement of the piston. On heating, the column of coal softened and contracted in length due to the plastic deformation under the action of piston. When the coal pencil softened, bubbles of gas were formed due to the decomposition of the softened coal mass. The gases released were trapped causing the coal column to swell up. The dilatation percent of the coal indicates its coking power. The results of dilatometric test are presented in Table 2.

Determination of total sulphur by Eschka method

1g of coal sample was weighed into a 30ml porcelain crucible and mixed with 3g of Eschka mixture (2 parts magnesium oxide and 1 parts anhydrous sodium carbonate). The mixture was again covered with 1g Eschka mixture. The blank and the standard samples were prepared in a similar manner. The crucibles were then placed in a cold muffle furnace and gradually heated to 800°C for about 60 minutes. The temperature was maintained for an additional 60 minutes. The crucibles were then removed, slightly cooled and stirred to ensure that no black particles remained. The crucibles were then emptied into 400ml beakers containing 100mls of hot water. Digestion was done for 45 minutes with occasional stirring. The solution in each beaker was then decanted through 540 filter paper into a 400 ml beaker. The filtrate volume was about 250ml. Three drops of methyl orange indicator was added. Sodium hydroxide was then added drop wise until just neutral. Then 1ml of hydrochloric acid was added to just acid after which 25ml of potassium sulphate was also added. The sample was thereafter heated to boiling and 10mls of barium chloride solution was slowly added with stirring. The solution was held at the temperature boiling for 30 minutes and allowed to cool to ambient temperature. The solution was then filtered with No 42 filter paper and washed well with hot water. The wet filter paper was thereafter placed into a crucible and ignited for 15 minutes. The paper was gradually smoked off in the muffle furnace in which the temperature was raised to 800 °C and maintained for 1hr. The crucible was cooled and barium sulphate weighed. The total sulphur content was calculated using the formula in equation (3).

$$S_t = \frac{A - B}{C} \, x \, 13.74 \qquad (3)$$

The results of sulphur analysis by Eschka method are shown in Table 1.

3. RESULTS AND DISCUSSION

3.1 RESULTS

The results of the analysis are presented in Tables 1 and 2.

Table 1: **Results of proximate analysis and free swelling index number on Nigerian and Polish Bellview coals**

S/NO	Parameters %	Enugu	Okaba	*Lafia	Bellview A	Bellview B
1.	Moisture	8.31	13.92	1.5	1.50	0.80
2.	Ash (ad)	7.23	7.64	25.60	5.71	6.05
3.	Ash (db)	7.89	8.88	25.99	5.80	6.10
4.	Volatile matter (ad)	46.14	50.74	22.60	29.51	29.16
5.	Volatile matter (db)	50.32	58.95	22.94	29.07	28.93
6.	Volatile matter (daf)	54.63	64.69	31.00	31.80	31.30
7.	Fixed carbon (daf)	45.37	35.31	69.00	68.20	68.70
8.	Sulphur (ad)	0.40	0.60	2.30	0.59	0.69
9.	Sulphur (db)	0.44	0.70	2.34	0.6	0.7
10.	Free swelling Index (FSI)	0	0	6	2.5	2.5

Note: ad – as determined, db – dried basis, daf – dried ash free
**determined under Dr. W.I.A. Aderonpe, NMDC, Jos*

Table 2: Coking properties of Polish Bellview coals

S/NO	Analytical Parameters	Bellview A	Bellview B
1.	**Gieseler Plastometery**		
	Softening temp (°C)	399	402
	Maximum fluidity temp (°C)	439	438
	Re-solidification temp (°C)	469	462
	Temperature range (°C)	70	60
	Maximum fluidity (ddpm)	48	38
2.	**Ruhr Dilatometry**		
	Softening temp (°C)	406	404
	Maximum contraction temp (°C)	440	439
	Maximum dilatation temp (°C)	463	462
	Maximum contraction %	26	24
	Maximum dilatation %	10	-7
	G-value coking capacity	0.97	0.93
	ISO code	522	521

Note: Both Enugu and Okaba coals have zero fluidity and dilatation

3.2 DISCUSSION OF RESULTS

The moisture contents of 8.31%, 1.50%, 1.50%, and 0.80% determined for Enugu, Lafia, Bellview A and B, respectively, fall below the maximum limit of 9% specified for coal blends for cokemaking at the Ajaokuta steel plant, Nigeria [10]. However, the moisture content of 13.82% determined for Okaba coal far exceeds this limit. It is also observed that the moisture contents of Bellview coals agree closely with the 1.50% to 2.20% determined for the Indian Jharia coal samples [3]. Hence, on the basis of moisture contents, all the coals, with the exception of Okaba coal can be considered suitable for inclusion in blends for cokemaking at the Ajaokuta steel plant.

The ash content of 7.23%, 7.64%, 5.71%, and 6.05% determined for Enugu, Okaba, Bellview A and Bellview B, respectively, also fall bellow the upper limit of 10% specified for coal blends at Ajaokuta [10]. But the ash content of 25.60% determined for Lafia coal exceeds this upper limit. The ash contents in Enugu, and Okaba coals fall within the range of 7.2% to 9.6% for main coals carbonized in Japan to produce coke [11], while the ash content of Bellview coals exceeds the 3.4% determined for the British Ogmore prime coking coal [12]. It is also noted that the ash contents of all the coals except Lafia coal fall below 20% to 25% for the Indian Jharia coal samples [3]. The ash content in the Canadian Hat Creek coal, 6.8%, exceeds the ash contents for the two Bellview coals samples [4]. It is therefore obvious that all the coals tested, except Lafia coal, satisfy the ash content requirement and may form proportion of blends to produce coke at Ajaokuta. However, Lafia coal can also participate in blends to the extent constrained by its high ash and sulphur contents.

The sulphur contents of 0.40%, 0.60%, 0.59% and 0.69% determined for Enugu, Okaba, Bellview A and Bellview B coals, respectively are lower than the upper limit of 0.9% specified for coals for cokemaking at Ajaokuta [10]. The sulphur content of 2.30% in Lafia coal far exceeds this upper limit. The sulphur content of 0.29% to 0.38% determined for typical Canadian coal blends are lower than for the coals tested. However, a blend with sulphur content as high as 1.04% has also been used in Canada [5]. The sulphur content of 0.20% determined for prime coking Ogmore coal is also far lower than for the coals tested [12]. The sulphur content of 0.71% to 0.95% in German Zentralkokeri Saar coal blend exceeds those of the coals tested, except Lafia coal [13]. On carbonization, only 50% to 60% of sulphur in the coals for cokemaking remain in the coke produced [1]. The low sulphur contents of Enugu and Okaba coals suggests their inclusion in blends with low sulphur Bellview coal to an extent constrained by their non-caking properties. However, the inclusion of Lafia coal in blends with Bellview coals will be constrained not only by its medium coking properties but also its high sulphur and ash contents.

The volatile contents of all the coals exceed the range of 27.70% to 30.30% (daf) specified for coal blends for cokemaking at Ajaokuta [10]. The volatile contents of the Bellview coals are however lower than 39.40 to 41.80% for high volatile coals carbonized in Japan [11] and 36% to 40% for Indian Jharia coal samples [3]. The successful carbonization of coals with volatiles exceeding 30.3% suggests that cokeable blends of Bellview coals with Enugu, Okaba and Lafia coals may be produced.

The free swelling index (FSI) number of 2.5 determined for the Bellview coals is lower than 3 to 8 for Indian coals and the average of 6.5 for a typical French coal blend for cokemaking [14]. The FSI of 4.5 for some German coal blends and 5.5. to 8.5 for Western Canada binary blends also exceed the 2.5 for Belleview coals. The FSI of 6 determined for Lafia coal exceed the 2.5 for Bellview coals and falls within the range of 3 to 8 for some Indian coals (14). The zero FSI for Enugu and Okaba coals show that the two coals are non-caking [15]. The FSI value of 2.5 for the Bellview coals also indicate that the coals are not of self-coking grade category with FSI exceeding 4.5 [15].

The free swelling number has been shown not to be a sufficient indicator of the cokeability of a coal. For example, a German blend with a FSI of 4 gave a dilatation of 13%, while a blend with a higher FSI of 4.5 gave a lower dilatation of 5%. Also, some South American coals with FSI of 3.5 to 4.5 produced only contraction of -30% to -10%, with no dilatation [1].

The Gieseler fluidity of 48 ddpm and 38 ddpm determined for Belleview A and B respectively, are lower than 27,000ddpm for Canadian Nova Scotian coals [5], 1000 to 1,500ddpm for Australian Illawara coal [16]. The softening temperature of 355^{0}C and re - solidification temperature of 462^{o}C determined for Lafia coal [12] overlaps those of Bellview coals. The Gieseler fluidity of Bellview coals exceed 3.7ddpm for Chinese Chenggyuan coal sample [17]. Thus, on the basis of Gieseler fluidity, Bellview coals may not be self-coking and its overlap with Lafia coal temperature range suggests that two coals can blend for cokemaking. The zero Gieseler fluidity for Enugu and Okaba coals show that the two coals will be infusible components in blends and thus reduce the micun strength of coke. Hence, the two coals can only blend with self-coking coals to a very limited extent.

The Ruhr dilatation of 10% and –7% determined for the Bellview coals A and B, are lower than 132.3% and 246.1% reported for Chinese Aieweieh and Wugong coals, respectively [17]. The dilatation of 10% for Belleview A falls within the range of 5% and 13% for coals reported by Echterhoff [13] that produced coal that almost satisfy micum requirements for blast furnace iron making .The G-value of 0.97 for Bellview A agrees closely with 0.954 to 0.973 determined for typical German coal blends for cokemaking [18]. Industrial carbonization studies has shown that micum indices do not always directly improve at the same rate with increasing dilatation %. For example, a coal that contracted only by -13% without any dilatation gave M10 and M40 of 5.6% and 73.6%, respectively, as against 5.8%, and 73%, for a coal with 5%. For a coal with 13% dilatation, the M10 and M40 indices of 6.2% and 76.4%, respectively, were determined [13]. It has also been shown that high dilatation percent does not always imply a correspondingly high Gieseler fluidity. For example, while the Chinese Aieweieh coal with 132.3% dilatation gave a Gieseler fluidity of only 990 ddpm, the Baiyang coal with 92% dilatation gave a higher Gieseler fluidity of 3,240ddpm [17]. However, Bellview A with higher dilatation of 10% gave a higher fluidity of 48 ddpm as against 38 ddpm for Bellview B with dilatation of –7%. The relatively high G-value coking capacity of 0.97 for Bellview A indicates that the coal may produce a metallurgical grade coke on carbonization. However, the relatively low dilatation percentage suggests that the coal may not accommodate the non-caking Enugu and Okaba in blends. The high ash and sulphur contents of Lafia coal may also disallow its inclusion in blends with Bellview A coal.

In summary, the analysis results have shown that Bellview A coal has a higher grade than B and may produce metallurgical grade coke on carbonization. However, the local coals from Enugu and Okaba are non-caking and their infusible nature may disallow them from blending with Bellview A. Lafia coal has been shown to be medium coking but with excessively high ash and sulphur content that may also disallow its inclusion in blends with Bellview A coal.

Blend formulation calculations showed that 26.38% of the high ash, high sulphur Lafia coal can blend with 48.64% of low ash, low sulphur UK Ogmore coal and 24.98% of Bellview A coal to produce a blend with an average ash, sulphur and volatile matter of 9.96%, 0.86% and 29.45%, respectively. It was also discovered that 16.63% Lafia coal can also blend with 59.22% of low ash, low sulphur Canadian coal to give a blend with an average ash, sulphur and volatile matter of 9.99%, 0.77% and 23.14%, respectively [5,12]. The former blend satisfy all the main requirement for cokemaking at Ajaokuta, while the latter satisfy all but the volatile content requirement of 27.7 – 30.30%. However, coals with volatiles of 22.30%, lower than for the second blend proposed have been carbonized to produce model coke in the former Czechoslovakia [19]. If the proposed blends are confirmed as cokeable by bench and pilot scale cokeability tests, cokemaking at Ajaokuta will be conducted with substantial input of the high ash, high sulphur Lafia coal. This will lead to lower cost in ironmaking and a sustainable growth of the national steel industry.

On the basic of International standard organization (ISO) classification, Bellview A is number 523 while B is 522 [15]. This parameter indicates that Bellview A is almost a self – coking coal, while Bellview B is a medium coking coal. The cokeability of the former can be improved during carbonization by methods such as pre-heating, partial briquetting and stamp charging.

4. CONCLUSIONS

An evaluation of the two coal samples imported for Ajaokuta steel company, Nigeria from Poland, show that the two coals- Bellview A and B, are low-sulphur, low ash, medium volatile coking coals of ISO codes 523 and 522, respectively. It has been shown that the two coals may not form cokeable blends with non-coking Nigerian coals. However, blend calculations indicates that cokable ternary blends of Bellview A and Lafia coals with prime coking low ash, low sulphur coals such as UK Ogmore may be possible. When the proposed blends are confirmed as cokeable a sustainable iron and steel making will become possible at Ajaokuta.

Where

S_t - total sulphur
A - mass of barium sulphate from sample
B - mass of barium sulphate from blank
C - mass of sample used
G - Coking capacity
E - Softening temperature (K)
V - temperature of maximum dilatation (K)
c - % maximum contraction
d - % maximum dilatation

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