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Numerical Computations to Produce Cokeable Coal Blends at The Ajaokuta Steel Plant, Nigeria

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ABSTRACT

A mathematical model and its associated numerical search algorithm has been developed for routine coal blending to include local coals for cokemaking at the Nigerian blast furnace-based Ajaokuta Steel Plant. A typical binary blend proposed using the model includes 28.38% and 29.00% of the ash- laden Lafia and non-caking Okaba coals, respectively. The proposed blends satisfy basic chemical and mechanical strength requirements at the lowest cost per ton of coal. The blending calculations showed that only low ash, low sulphur, medium volatile and high vitrinite reflectance prime grade coals such as the UK Ogmore should be imported for blending with the ash-laden medium coking Lafia coal. When the proposed blends are successfully confirmed with bench and pilot scale carbonization tests, cokemaking at Ajaokuta will be conducted with substantial savings in foreign exchange.

Keywords*: model, coal, blending, cokemaking, blast furnace*

1.0 INTRODUCTION

Metallurgical coke is a solid coherent and brittle material obtained by carbonizing bituminous prime coking coals in the coke oven plant. In the blast furnace, coke serves as a reducing agent and supply the major part of the heat required for the ironmaking process. It is also the only solid material below the smelting zone and thus supports the overlying burden and provides a permeable column for reducing gases [1]. The bituminous prime coking coals suitable for straight carbonization accounts for only about 5% of the world's supply of coals [2]. This problem has made blend carbonization of prime coking coals with poorly coking coals a common practice worldwide.

The Nigerian local coal deposit is estimated to be about 1.5 billion tons. Unfortunately, tests conducted on these coal deposits showed that most of them are non-caking. Lafia coal, the only local coal with good coking properties, is however, laden with excessive ash and sulphur contents of about 26.30% and 2.30%, respectively [3]. The Lafia coal deposit has been found to be geologically faulty and the minimum estimated cost of mining it per ton was put at N87.50 as at 1977 [3]. Considering the present exchange rate of the Nigerian Naira to the US dollar, the current mining price per ton of Lafia coal can be taken to be US$ 87.50.

For cokemaking, coal blends are required to have specified range of values for volatile matter, ash and sulphur contents [4]. Excessive ash increases the volume of slag in the blast furnace, and reduces its operating efficiency. Sulphur in the coke gets into the iron and reduces its mechanical strength, while very high volatile generally reduce coke output [5] .

On completion of its first phase, Ajaokuta steel plant is expected to import its 1.3 million tons of coking coals annually. Considering the huge sum in foreign exchange required, there is an urgent need to obtain cokeable blends including appreciable amounts of local coals. The current high international price of about US$ 300 for coking coals per ton makes coal blending optimization and co-carbonisation with cheaper poorly coking coals more urgent [6]. Blend formulations by numerical computations on the basis of a mathematical model have been employed in the steel industries [7, 8].

The analysis results on Nigerian coals (i.e Okaba and Lafia) were obtained from the tests conducted at the National Metallurgical Development Centre (NMDC), Jos, Nigeria. The analysis data on the UK Ogmore and the Canadian coals were obtained from literature [9, 10]. The values of average vitrinite reflectance were estimated for coals for which it was not available from a curve of Rmax versus volatile matter (daf) [11]. The prices per ton of coals used in the calculations were estimated based on information obtained from literature [6, 12].

In the bisection method, an appropriate value for the exact solution of a non-linear equation f(x)=0 in the interval [a,b] of interest is obtained by a systematic reduction of this interval through a process of successive halving of the interval containing the desired root[13]. The aim of this research paper is to apply the concept of bisection search to obtain blend mixtures of high and low grade coals that will meet the specifications for metallurgical cokemaking at the Nigerian Ajaokuta Steel Plant.

2.0 THEORETICAL ANALYSIS

2.1 Co-ordinate Geometry

Analytical geometry refers to the representation of the points in the dimensional space by ordered set of n or more numbers, called co-ordinates [14]. In two-dimensional geometry (X – Y axes), the position of a point in a plane may be specified by its distances from two fixed perpendicular lines; the axes. The Cartesian co-ordinates are also called rectangular co-ordinates. There are also affine co-ordinates where three axial planes meet by pairs in three axes OX, OY and OZ. In solid geometry, we deal with solids such as a sphere, pyramid and a cylinder. A sphere is a solid such that every point on its surface is at an equal distance from the same point, its centre. In space geometry, sphere corresponds to a circle in plane geometry. The locus of a point is the path traced out by a point, which moves under certain conditions. The point may move in a plane or in space, and the Cartesian equation of the locus can be obtained; that is, the connection which exists between X and Y, or (X,Y,Z in space), the co-ordinates of the point referred to perpendicular axes.

2.2 Mathematical Modeling

Basically, mathematical modeling uses analogy to aid the understanding of complex systems. Analogy helps to explain unfamiliar situations. Modeling affords the opportunity to refine and improve our qualitative and quantitative understanding of a particular system or process. In the design of new, larger or otherwise modified existing processes or systems, mathematical modeling has proved invaluable in a large number of industries [15].

Using linear programming, the coal blending problem can be formulated mathematically as follows:

Minimize:

$$C = X_1 C_1 + X_2 C_2 + C_3 + \ldots + X_n C_n$$

Subject to:

$$X_1 R_1 + X_2 R_2 + X_3 R_3 + \ldots + X_n R_n \geq 1.15 \qquad (1)$$

$X_1 V_1 + X_2 V_2 + X_3 V_3 + \ldots + X_n V_n > 30.3$ (2)

$X_1 V_1 + X_2 V_2 + X_3 V_3 + \ldots + XnVn < 27.7$ (3)

$X_1 S_1 + X_2 S_2 + X_3 S_3 + \ldots + X_n S_n \leq 0.9$ (4)

$X_1 A_1 + X_2 A_2 + X_3 A_3 + \ldots + X_n S_n \leq 10$ (5)

$X1+X2+ \ldots + X_n = 1$ (6)

Where:

$X_1, X_2, \ldots X_n$ = are proportions of coals 1,2,. . .n in blend

R = vitrinite reflectance of coal

V = volatile matter content

S = sulphur content

A = Ash content

C = cost per ton of coal

2.3 Application of Co-ordinate Geometry to Coal Blend Formulations

Plane and space geometries can be used to represent various blend formulations.

2.3.1 Binary Blend Formulations

A binary blend must satisfy the following conditions:

i. It consists of two coals

ii. The two coals must blend such that the proportions of each coal add to 1 (unity condition) and $X_1, X_2 \geq 0$.

iii. The chemical requirements and strength requirements in terms of vitrinite reflectance must be satisfied. A set of points about the origin in the first quadrant of a rectangular co-ordinate such that the radius, always equal 1, will satisfy conditions 1 and 2 (Fig 1). Therefore:

$X_1 = r \cos \theta$

$X_2 = r \sin \theta$

By Pathagoras' theorem, the Cartesian equation representing the locus of point B in the

X – Y rectangular co-ordinate is obtained as follows:

$(r \cos \theta)^2 + (r \sin \theta)^2 = r^2$

$$\cos^2 \theta + \sin^2 \theta = 1 \qquad (7)$$

Therefore,

$X_1 = \cos^2 \theta$

$X_2 = \sin^2 \theta$

mathematically describes the locus of the points which is an arc of a unit radius in the first quadrant. The third condition will be satisfied by a numerical search of the interval $0 \le \theta \le {}^{\pi}/_2$ on the locus.

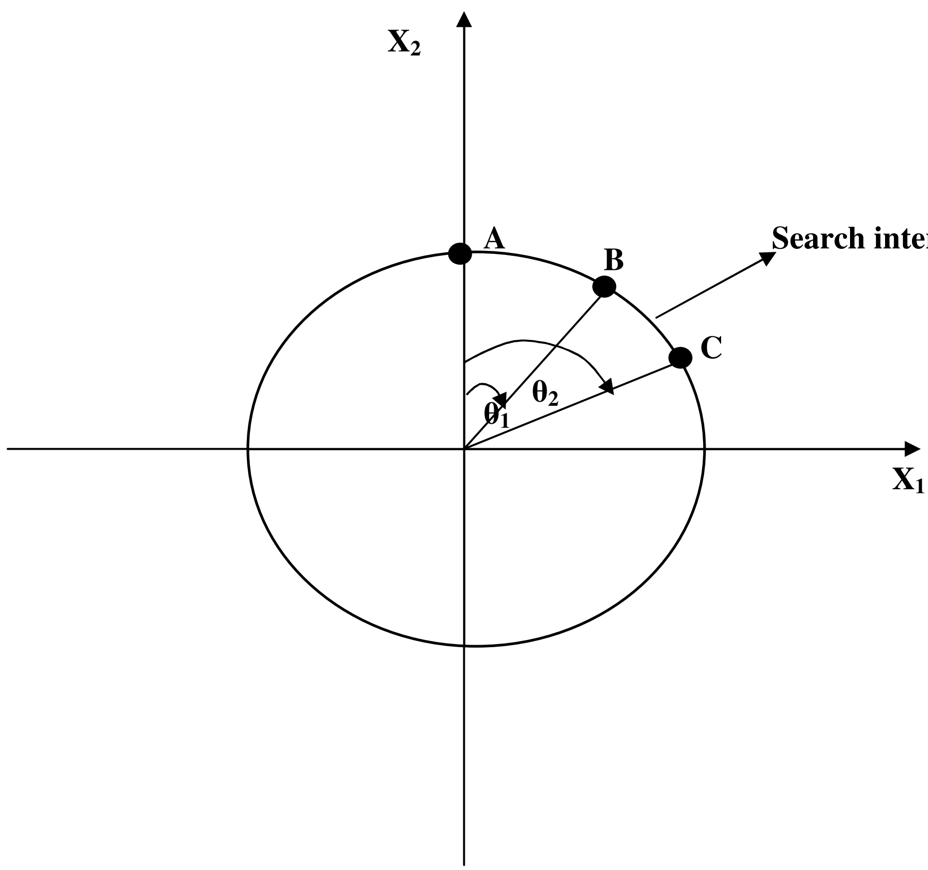

Fig. 1: Loci of unit radius in bisection numerical search for optimum θ in binary coal blending

2.3.2 Ternary Blend

Since a sphere corresponds to a circle in space geometry, a ternary coal blend can be represented by the spherical co-ordinates (X, Y, Z) [16] such that:

i. A point B is defined by (r, θ, β) where the radius $r = 1$ unit and

$0 \leq \theta \leq \pi/2$

$0 \leq \beta \leq \pi/2$

ii. From geometrical analysis, the point B can be represented by the following equations [16]:

$x = r \sin\theta \cos\beta$

$y = r \sin\theta \sin\beta$

$z = r \cos\theta$

such that $r^2 \cos^2\theta + r^2 \sin^2\theta \cos^2\beta + r^2 \sin^2\theta \sin^2\beta = r^2$ (8)

where

X_1 = proportion of coal 1 in blend = $\cos^2\theta$

X_2 = proportion of coal 2 in blend = $\sin^2\theta \cos 2\beta$

X_3 = proportion of coal 3 in blend = $\sin^2\theta \sin^2\beta$ and

$r = 1$

The spherical surface bounding the region is the locus of point B.

When $\beta = \theta$

$X_2 = ¼ \sin^2 2\theta$

$X_3 = \sin^2\theta \sin^2\theta$

$= \sin^4\theta$

such that:

$0 \leq \theta \leq \pi/2$ and $0 \leq \beta \leq \pi/2$

2.3.3 Quaternary Blend

The quaternary blend can be deduced from the binary blend as follows:

$$(\cos^2 \theta + \sin^2 \theta)(\cos^2 \theta + \sin^2 \theta) = 1$$

$$\cos^2 \theta \cos^2 \theta + \cos^2 \theta \sin^2 \theta + \cos^2 \theta \sin^2 \theta + \sin^2 \theta \sin^2 \theta = 1$$

Therefore:

$$\text{Cos}^4 \theta + \cos^2 \theta \sin^2 \theta + \cos^2 \theta \sin^2 \theta + \sin^4 \theta = 1 \quad (9)$$

Where:

$X_1 = \cos^4 \theta$

$X_2 = X_3 = \cos^2 \theta \sin^2 \theta$

$= \frac{1}{4} \sin^2 2\theta$

$X_4 = \sin^4 \theta$

such that

$0 \leq \theta \leq \pi/2$

2.3.4 Higher Blends

Blends of 5 and 6 coals can be similarly deduced from ternary and binary blends and the resulting equations are:

$$\cos^4 \theta + \frac{1}{4} \sin^2 2\theta + \cos^2 \theta \sin^4 \theta + \cos^2 \theta \sin^2 \theta + \sin^6 \theta = 1 \quad (10)$$

$$\cos^4 \theta + \cos^4 \theta \sin^2 \theta + \cos^2 \theta \sin^4 \theta + \cos^2 \theta \sin^2 \theta + \cos^2 \theta \sin^4 \theta + \sin^6 \theta = 1 \quad (11)$$

for blends with 5 and 6 coals, respectively.

2.4 Direct Search for Optimum

The method of binary division of search interval was used to determine the optimum cost of the various blends. The basic features are as follows:

2.4.1 The search Constraints

The search in a direction is reversed for any of the following conditions:

$\Delta R < 0$ – vitrinite reflectance constraint

$\Delta A \geq 0$ – ash content constraint

$\Delta V_L < 0$ - volatile matter constraint (lower limit)

$\Delta V_U > 0$ – volatile matter constraint (upper limit)

$\Delta S \geq 0$ – sulphur content constraint

For the bisection search of a linear solution interval, the absolute error ()r) in the determination of the solution cannot exceed half the length of the search interval [17], that is:

$$\Delta r < 0.5(\theta_C - \theta_B)$$

where

$\theta_C =$ upper bound of the search interval

$\theta_B =$ lower bound of the search interval

2.4.2 Pseudo-code for the bisection method in coal blending

Step 1: select prime grade coal (X1) such that:

R1> 1.15, A1 <10%, V1 <30.3% ,S1< 0.9%

Step 2: select low -grade coals

Step 3: initialize

Step size, h= 10, X1= 1.0, allowable error (e) = 0.5^0

Evaluate: R, A, S, V,C, ΔR, ΔA, ΔS, ΔV

Counters:m=0,n=0, p=0, q=0

Step 4: IF (ΔR >0 AND ΔA<0 AND ΔV_u<0 AND ΔS<0) THEN

Set:$\theta = \theta + h$, m= m + 1

Evaluate: X1, X2…Xn

Evaluate: R, A, V, S, ΔR, ΔA, ΔS, ΔV

ELSE

Set: $\theta = \theta + h$, $n = n + 1$

Evaluate: X1, X2…Xn

Evaluate: R,A,S,V,C, ΔR, ΔA, ΔS, ΔV

ENDIF

Step 5: IF($\Delta R > 0$ AND $\Delta A < 0$ AND $\Delta V_u < 0$ AND $\Delta S < 0$ AND$\Delta V_L > 0$) THEN

Set: $\theta = \theta + h$, $p = p + 1$

Evaluate: X1, X2…Xn

Evaluate: R, A, V, S, ΔR, ΔA, ΔS, ΔV

ENDIF

Step 6: IF ($p > 1$ AND ($\Delta R \leq 0$ OR$\Delta A \geq 0$ OR $\Delta V_u \geq 0$ OR$\Delta S \geq 0$)) THEN

Set: $\theta = \theta + r(h/2^q)$, $q = q + 1$, $r = -1$

Evaluate: X1, X2…Xn

Evaluate: R, A, V, S, ΔR, ΔA, ΔS, ΔV

ELSE

Set: $\theta = \theta + r(h/2^q)$, $q = q + 1$, $r = 1$

Evaluate: X1, X2…Xn, Evaluate: R,A,V,S, ΔR, ΔA, ΔS, ΔV

ENDIF

Step 7: IF ($\Delta r < e$) STOP

3.0 RESULTS AND DISCUSSION

3.1 RESULTS

The analytical results of proximate analysis of coals obtained from literature are presented in Table 1, while the results of some blend calculations are presented in Tables 2 and 3.

Table 1: Parameters of coal for blending calculations

S/N	Parameters	Ogmore coal	Canada coal	Lafia coal	Okaba coal
1	Avg. vitrinite reflectance (R_{max})	1.20	1.52	1.20	0.40
2	Ash (dried basis)	3.40	7.20	26.30	7.32
3	Volatile matter (dried ash free)	27.40	17.40(db)	32.20	68.78
4	Sulphur (dried basis)	0.20	0.39	2.30	0.66
5	Cost/ ton (US$)	300	300	87.5	34

Table 2: Binary blending of UK Ogmore and Nigerian high ash, high sulphur Lafia coal

θ	q	Ogmore	Lafia	R	A	V	S	C	Δr	cv
0		1.0000	0	1.20	3.4	27.40	0.20	300	-	V
10	m=1	0.9698	0.0302	1.20	4.09	27.54	0.26	293.58	-	V
20	P=1	0.8830	0.1170	1.20	6.08	27.94	0.45	275.14	<5	N
30	P=2	0.750	0.2500	1.20	9.13	28.60	073	246.88	<5	N
40	q=1	0.5868	0.4132	1.20	12.86	29.38	1.07	212.20		A,S
35	q=2	0.6710	0.3299	1.20	10.93	28.98	0.89	230.09		A
32.5	q=3	0.7113	0.2887	1.20	10.01	28.79	0.81	238.65		A
31.25	q=4	0.7309	0.2691	1.20	9.56	28.69	0.77	242.82	<0.63	N
31.875	q=5	0.7211	0.2789	1.20	9.79	28.74	0.79	240.73	<0.32	N
32.1875	q=6	0.7162	0.2838	1.20	9.90	28.76	0.80	239.69	<0.16	N

Note: cv = constraints violated, N= none

Table 3: Ternary blending of UK Ogmore, Nigerian Okaba and Lafia coal

θ	q	Ogmore	Okaba	Lafia	R	A	V	S	C	Δr	c v
0		1.0000	0	0	1.20	3.4	27.40	0.20	300		V
10	p=1	0.9406	0.0009	0.0585	1.20	4.74	27.72	0.32	287.33		N
20	p=2	0.7797	0.0137	0.2066	1.19	8.18	28.96	0.64	252.45	<5	N
30	q=1	0.7660	0.1707	0.0633	1.06	5.52	34.76	0.41	241.14	<5	R,V
25	q=2	0.6747	0.0319	0.2934	1.17	10.24	30.12	0.83	229.19		A
22.5	q=3	0.7286	0.0214	0.2500	1.18	9.21	29.49	0.73	241.18		N
23.75	q=4	0.7019	0.0263	0.2718	1.18	9.73	29.79	0.78	235.25	$<0.6^0$	N
24.375	q=5	0.6884	0.0290	0.2826	1.18	9.99	29.96	0.81	232.23	$<0.31^0$	N

Note: cv = constraints violated, N= none

3.2 DISCUSSION OF RESULTS

The ash, volatile matter and sulphur content of 26.30%, 32.20% and 2.30% respectively, determined for Lafia coal exceeds the upper limits of 10%, 30.3% and 0.9%,respectively, specified for cokemaking at the Ajaokuta Steel Plant [4]. The coking properties- Gieseler plastometry, crucible swelling number and Ruhr dilatometry are however not specified for coals to be carbonized at Ajaokuta. Considering the excessive ash, volatile and sulphur contents of Lafia coal, blend carbonization with low ash and low sulphur bituminous coals will be necessary.

The numerical blend design gave optimal volatile contents of 28.76%, 29.96% and 28.85%, respectively, for the proposed binary, ternary and quaternary blends including Lafia coal. These volatile contents fall within the range specified for cokemaking at Ajaokuta [4]. For cokemaking in the former Czeckoslovakia, coals with much lower volatiles of 22.3% had been used [18]. In India, coals with a much lower volatile of 21.20% had been successfully carbonized to produce coke [19]. For cokemaking at France's Usinor plant, coal blends with 24% to 26% volatiles had been used [20]. Coals with volatiles of 39.4% to 41.8% that far exceed the average volatile contents of blends including Lafia coal has been reported to produce coke in Japan [21]. In Germany, some lower volatile coals were found to produce coke with lower micum indices [22]. The three blends obtained for Lafia coal may thus produce coke on carbonization.

Ash contents of 9.90%, 9.99% and 9.63% determined, respectively for the proposed binary, ternary and quaternary blends including Lafia coal, falls below the upper limit of 10% for cokemaking at Ajaokuta [4]. At the France Usinor plant, coals with lower ash content of 7% to 8% have been carbonized to produce coke [20]. However, in India coals with higher ash content of 17.52% has been successfully used to produce coke [19]. The three blends proposed including Lafia coal therefore have acceptable ash contents and may produce metallurgical grade coke on carbonization.

The average sulphur contents of 0.80%, 0.81% and 0.64%, determined respectively for the proposed binary, ternary and quaternary blends including Lafia coal fall below the upper limit of 0.9% specified for cokemaking at Ajaokuta [4]. The sulphur content of 0.27% to 0.38% determined for typical Canadian coal blends are lower than the sulphur contents of the proposed blends [10]. However, the sulphur content of up to 0.95% determined for German Zentral-Kokerei Saar coal blends exceed 0.81% which is the highest sulphur content for the proposed blends [23]. A low sulphur content is not an indication of the degree of maturity of coals as shown by the very low sulphur content of 0.21% determined for the low rank Australian Yallourn coal [24]. The sulphur contents of the proposed blends thus agree with the international standard practice for cokemaking and may produce coke with acceptable sulphur contents.

The average vitrinite reflectance(R_{max}) of 1.2, 1.18 and 1.15 determined, respectively, for the proposed binary, ternary and quaternary blends including Lafia coal agree with the minimum of 1.15 for coal blends typically in use for carbonization in the United States of America [8]. The R_{max} of 1.28 determined for the Australian Illawarra coal is higher than 1.18 for the proposed ternary blend [25]. Coal blends with R_{max} of 1.04, which is lower than for the proposed blends have been reported to produce coke with M10 and M40 of 11.4% and 82.2%, [26]. The Illawarra coal produced coke with M10 and M40 of 8% and 82%, respectively. On the basis of the R_{max} of the proposed blends, there is a strong indication that the proposed blends will produce coke with M10 and M40 values that meet the specifications of 9% (maximum) and 78% (minimum) respectively, for coke to be used in the blast furnace at Ajaokuta [4].

The inclusion of 28.38%, 28.26%, and 10.81% of Lafia coal in binary, ternary and quaternary blends were found to produce optimal blends that satisfy the chemical properties and mechanical strength requirements at the lowest possible estimated costs of US$239.69, US$ 232.23 and US$ 191.80, respectively; for the three proposed blends when the average cost of a prime grade coal is taken as US$ 300 per ton [6]. The proposed blends yield a reduction in cost per ton of cokeable coal of US$ 60.31, US $67.77 and US$ 108.20 , respectively; in comparison with direct carbonisation of prime grade coal. Also, 2.90% of non-caking Nigerian Okaba coal was included in ternary blend.

The 28.38% of Lafia coal proposed for the binary blend agree closely with the 28% determined for bench scale blending of Lafia with 49% UK Ogmore prime coking coal and 13% non-caking Nigerian Enugu coal [9]. The proposed blends need to be subjected to bench and pilot scale studies prior to industrial scale cokemaking. A successful application of these blends at the Ajaokuta steel plant may save about US$ 78.40 million, US$ 88.10 million and US$ 140.60 for the proposed binary, ternary and quaternary blends respectively; on annual importation of 1.3 million tons of prime coking coal at the completion of Ajaokuta's first phase. This expected reduction in cost is significant considering the relatively high cost per ton of US$ 87.50 estimated for Lafia coal and US$ 34 for the non-caking local coals. The model also ensured that the excessively high ash and sulphur contents of Lafia coal are not a hindrance to its use in cokemaking.

4.0 CONCLUSIONS

A mathematical model has been elaborated on the basis of analytical geometrical representation of coal blend components. The model has been applied to propose blends including up to 28.38% and 29.00% of high ash Nigerian Lafia and non-caking Nigerian Okaba coals, respectively. The proposed blends will produce significant reduction in the cost of cokemaking at Ajaokuta when confirmed by bench and pilot scale carbonization tests

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