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MATHEMATICAL OPTIMIZATION OF NON-COKING COAL INCLUSION IN COKING BLEND FORMULATIONS

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Abstract

Blend formulation to maximize the inclusion of non-coking coals with the scarce and expensive coking coals is an essential practice in the steel industry. This study demonstrated the use of Microsoft Excel based on a blending model to obtain probable cokeable blends between sample prime coking coals and non-coking Nigerian Lafia-Obi and Okaba coals; having high ash/sulphur and high volatile, respectively. The results obtained showed that optimal binary, ternary and quaternary probable cokeable blends are possible. A cokeable binary blend of 64.51% low volatile, high vitrinite reflecting Western Canada prime coking coal and 35.49% Okaba coal with a cost reduction per ton of $61.56 was obtained. Also, a ternary blend of 74.04% medium volatile prime coking UK Ogmore coal produced an optimal cokeable blend including 19.22 and 6.74 percents of Lafiia-Obi concentrate and Okaba (as-received); respectively with a saving in cost per ton of $39.05. Furthermore, a quaternary blend comprising 40.35, 23.17, 23.17 and 13.30 percents of low volatile Canada, medium volatile Ogmore, Lafiia-Obi concentrate and Okaba (as-received); respectively with a saving in cost per ton of $56.06 was realized. The results obtained showed that vitrinite reflectance, coal beneficiation to reduce ash and sulphur contents and the use of a high volatile coal as a blend component are critical factors in obtaining probable cokeable blends. If the lowest cost binary blend proves cokeable in confirmatory tests, the significant cost reduction of about 29.31% achievable will make cokemaking more economical and sustainable.

Keywords: Coal, blend; binary, cokeable; cost; cokemaking.

1. Introduction

Coal is a combustible sedimentary organic rock which is composed mainly of carbon, hydrogen and oxygen. It is formed from vegetation which has been consolidated between other rock strata and altered by the combined effects of pressure, temperature and bacteria over million of years to form the coal seams [1, 2].

Bituminous coking coals required for the production of metallurgical coke is scarce worldwide and is in high demand in the face of rising steel production. For example on a yearly basis, British Steel procures 7.4 million metric tons of coking coal, while the blast furnace based Nigerian Ajaokuta integrated steel plant is estimated to use 1 million tons of the same coal grade on completion of its first phase. Coking coal is converted to coke by crushing it and then heating it in coke ovens at a temperature of about 1250ºC for about 18 hours [3, 4]. Coals are ranked on the basis of volatile matter contents. It has been reported that medium volatile coals (volatile contents in the range 27.70 to 30.30%) will produce good coke, while coke from high volatile coals are weak and highly reactive. Low volatile coals on the other hand produce dangerously high pressures than can cause irreparable damage within the coke oven [4, 5].

Moisture, ash, sulphur, phosphorous and alkalies are undesirable in coke as they have adverse effects on energy requirements, blast furnace operations, hot metal quality and/or refractory lining. Ash and sulphur in coke are usually restricted to lower than 10 and 0.80%, respectively. Unfortunately, Lafia-Obi coal, the only medium coking Nigerian coal has intolerably high ash and sulphur contents of up to 26 and 2.34% , respectively. Okaba coal is a high volatile sub-bituminous coal found in the proximity of the Ajaokuta Steel plant, Nigeria [7, 8, 9, 10, 11].

The average reflectance of vitrinite maceral and more importantly the nature of its distribution are critical indicators of the strength of the resulting coke. A cokeable coal is expected to have a vitrinite reflectance of at least 1.15 but ideally 1.25 to 1.35% with a unimodal vitrinite reflectance distribution [4]. The Western Canada coal has been reported to have very high vitrinite reflectance of 1.52% [12]. In addition to rank parameters, dilatation and fluidity properties of coals also provide empirical measures on the extent of softening and fusion on heating of coals to produce coke [3, 13]. Coal blending has been used for many years to obtain blends of desired properties from one or more coals. Metallurgical coke for use in very large blast furnaces must have very high strength in terms of hardness and stability of 68 and 55% respectively [14].

Blending of coals has been an important problem in integrated steel plants and mathematical models have been developed to facilitate it. Vasko [15] developed a model based on a mixed linear programming and binary decision tree analysis to obtain cokeable blends. The model results are used at the pilot scale oven for testing and validating the recommended blends. Skerl [16] developed an optimization model that proposes least cost set of blends on the basis of input desired coke properties. Adeleke and Onumanyi [17] elaborated an optimization model that obtains coal blends with derived formulae and used a binary search technique to determine the combination of coals that satisfy basic chemical and vitrinite reflectance at the least possible cost.

The aim of this study is to use the Microsoft Excel implementation of the optimization model of Adeleke and Onumanyi (2007) to demonstrate the significance of average vitrinite reflectance, ash/sulphur contents of the base prime coking coals in obtaining cokeable blends with a high ash/sulphur coal such as Lafia-Obi coal and its concentrate.

2. Methods

2.1 Analysis data

The data on proximate analysis of the Western Canada, UK Ogmore, Nigerian Lafia-Obi (as-received), Lafia-Obi leached concentrate and Okaba coal as received were obtained from Price *et al* [12], Ndaji and Marsh [18], Adeleke [19] and Laditan [20]; respectively. The volatile matter (dried ash free) of the Western Canada coal was calculated with a moisture content of 1% typical of coking coal according to Moitra *et al* [21]. The data on vitrinite reflectance for Ogmore coal was estimated [22], while those of Lafia-Obi and Okaba coals were obtained from Laditan [20]. The information on cost per ton of coal in the international market and transport cost was obtained from Energy Information Administration [23], HB Industry Report [24] and New York Times [25]. The data on proximate analysis, average vitrinite reflectance and cost per ton of coals used in sample blend optimization are presented in Table 1.

Table 1: Coal properties' data for coals used in sample blend formulations

Blend parameters	Ogmore coal	Canada coal	Lafia-Obi coal	Lafia-Obi concentrate	Okaba coal
Vitrinite reflectance (Average)	1.2	1.52	1.2	1.2	0.48
Ash (db)	3.4	7.2	33.73	20.55	11.60
Volatile matter (daf)	27.4	18.75	27.98	21.71	
Sulphur (db)	0.20	0.39	1.33	0.55	1.21
[1]Cost/ton ($)	210	210	60.33	67.64	36.55

2.2 Optimization method

The iteration elaborated by Adeleke and Onumanyi (2007) was implemented with Microsoft Excel, 2003.

3. Results and Discussion

The probable cokeable blend results obtained are presented in Tables 2 to 4.

The average contents of vitrinite maceral reflectance, ash, sulphur and volatile matter for the coal blends were determined using the formulae derived by Adeleke and Onumanyi [17] and according to a conventional practice reported by Skerl [16]. Binary blending of the prime coking western Canadian coal and the high ash, high sulphur Nigerian Lafia-Obi coal (as-received) gave an optimal blend that satisfy all the constraints except the requirements of volatile contents to lie between 27.70% and 30.30% [17]. However, the binary blending of the Canadian coal with the high volatile sub-bituminous Nigerian Okaba coal (as-received) gave an optimal blend comprising of 64.51 and 35.49 percents of the former and latter coal respectively. The average vitrinite reflectance of 1.15% was obtained for the blend, while the average ash and sulphur contents obtained are 1.24 and 0.12 percents below the upper limits allowable [9, 11]. The saving in cost per ton of blend was estimated to be $61.56. Further binary blending of the Canadian coal with the Lafia-Obi coal concentrate yielded an optimal blend of 79.12 and 20.88 percents of the former and latter; respectively and with a lower cost saving per ton of $29.73. The results obtained indicate that a high volatile coal such as Okaba may be an essential input in obtaining coal blends with acceptable levels of volatiles that minimize coke oven pressures during carbonization.

Ternary blending of the prime coking Canadian coal, Lafia-Obi coal (concentrate) and Okaba coal as-received gave a blend containing 74.76, 18.87 and 6.37 percents of Canada, Lafia-Obi (concentrate) and Okaba (as-received); respectively with a very low sulphur of 0.47% and high average vitrinite reflectance of 1.39% but could not satisfy the volatile requirements. Similarly, the ternary blend with the Lafia-Obi (as-received) yielded a blend that could not satisfy the volatile requirements and with a cost reduction per ton of $17.82 much lower than $37.92 for the former case. However, a ternary blend of medium volatile prime coking UK Ogmore coal produced an optimal cokeable blend consisting of 74.04, 19.22 and 6.74 percents of Ogmore, Lafiia-Obi concentrate and Okaba (as-received); respectively with a saving in cost per ton of $39.05. A quaternary optimal blend comprising 40.35, 23.17, 23.17 and 13.30 percents of low volatile Canada, medium volatile Ogmore, Lafiia-Obi concentrate and Okaba (as-received); respectively, that satisfy the basic chemical and coke strength requirements (as indicated by average vitrinite reflectance) with a saving in cost per ton of $56.06 was also obtained. The blend also has good average vitrinite reflectance of 1.23% and low sulphur of 0.32% [16]. These results showed that a medium volatile prime coking coal may be required to produce cokeable coal in combination with some coals. The cleaning of Lafia-Obi coal must have enhanced its inclusion in the ternary and quaternary blends.

The optimal cokeable blends obtained have to be subjected to petrographic analyses to determine the frequency distribution of the vitrinite reflectance and technological tests such as Gieseler plastometry and Ruhr dilatometry to confirm their cokeability prior to pilot scale tests. A cokeable blend is required to demonstrate unimodal vitrinite reflectance frequency distribution, a Ruhr G-value that fall in the range 1.05 to 1.10 and a Gieseler maximum fluidity of ≥ 300 ddpm [3, 4, 9]. The behaviour of the blends in term of coking pressure generation also needs to be examined [9].

4. Conclusion

The optimized coal blends obtained with the inclusion of non-coking Nigerian coals showed that probable cokeable blends at minimum costs could be obtained at binary blend of 64.51% low volatile, high vitrinite reflecting Western Canada prime coking coal and 35.49% and a quaternary blends containing 74.04% medium volatile, medium vitrinite reflecting UK Ogmore coal, 19.22% Lafia-Obi concentrate and 6.74% high volatile, low vitrinite reflecting Okaba coal (as-received). The cost reduction per ton of $61.56 obtained for the binary blending far exceeded that of quaternary blend by $22.51. The results obtained showed that vitrinite reflectance, coal beneficiation to reduce ash and sulphur contents and the use of a high volatile coal as a blend component are critical factors in obtaining probable cokeable blends. If the lower cost binary blend proves cokeable in confirmatory tests, the significant cost reduction of about 29.31% achievable will make ironmaking by the blast furnace route economical and sustainable.

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Table 2: Binary blending of Western Canada coking coal (WCAN) and Okaba coal (as-received) (OKA)

Ɵ	WCAN	OKA	R	A	V	S	C	R1	A1	V1	V2	S1	C1
0	1	0	1.52	7.2	18.75	0.39	210	0.37	-2.8	-8.95	-11.55	-0.41	0
10	0.969839	0.030161	1.488632	7.33271	19.55682	0.414732	204.7685	0.338632	-2.66729	-8.14318	-10.7432	-0.38527	5.2315
20	0.882993	0.117007	1.398313	7.71483	21.87993	0.485946	189.7052	0.248313	-2.28517	-5.82007	-8.42007	-0.31405	20.29484
30	0.749941	0.250059	1.259939	8.300259	25.43907	0.595048	166.6273	0.109939	-1.69974	-2.26093	-4.86093	-0.20495	43.3727
40	0.586735	0.413265	1.090204	9.018366	29.80484	0.728877	138.3192	-0.0598	-0.98163	2.10484	-0.49516	-0.07112	71.68082
35	0.670936	0.329064	1.177773	8.647883	27.55247	0.659833	152.9238	0.027773	-1.35212	-0.14753	-2.74753	-0.14017	57.07621
37.5	0.629328	0.370672	1.134501	8.830959	28.66549	0.693951	145.7069	-0.0155	-1.16904	0.965488	-1.63451	-0.10605	64.29314
36.25	0.650275	0.349725	1.156286	8.738791	28.10515	0.676775	149.3401	0.006286	-1.26121	0.405153	-2.19485	-0.12323	60.65986
36.875	0.639834	0.360166	1.145428	8.784729	28.38443	0.685336	147.5293	-0.00457	-1.21527	0.68443	-1.91557	-0.11466	62.47073
36.5625	0.645063	0.354937	1.150866	8.761722	28.24456	0.681048	148.4362	0.000866	-1.23828	0.544561	-2.05544	-0.11895	61.5638
36.71875	0.642451	0.357549	1.148149	8.773216	28.31444	0.68319	147.9831	-0.00185	-1.22678	0.614439	-1.98556	-0.11681	62.01689

Table 3: Ternary blend of UK Ogmore (OGM), Lafia-Obi concentrate (LFC) and Okaba coal (as-received) (OKA)

Ɵ	OGM	LFC	OKA	R	A	V	S	C	R1	A1	V1	V2	S1	C1
0	1	0	0	1.2	3.4	17.4	0.2	210	0.05	-6.6	-10.3	-12.9	-0.6	0
10	0.969839	0.029252	0.00091	1.199345	3.909127	27.65516	0.211157	205.6779	0.049345	-6.09087	-0.04484	-2.64484	-0.58884	4.322064
20	0.882993	0.103316	0.013691	1.190143	5.284137	28.49086	0.249988	192.9173	0.040143	-4.71586	0.790861	-1.80914	-0.55001	17.08274
30	0.749941	0.187529	0.062529	1.154979	7.12887	30.06202	0.32879	172.4576	0.004979	-2.87113	2.362022	-0.23798	-0.47121	37.54241
40	0.586735	0.242477	0.170788	1.077033	8.958943	32.46988	0.457363	145.8578	-0.07297	-1.04106	4.769876	2.169876	-0.34264	64.14221
35	0.670936	0.220781	0.108283	1.122036	8.074318	31.1615	0.38664	159.7879	-0.02796	-1.92568	3.461502	0.861502	-0.41336	50.21213
32.5	0.711242	0.205377	0.083381	1.139966	7.605932	30.58507	0.356097	166.3002	-0.01003	-2.39407	2.885068	0.285068	-0.4439	43.69983
31.25	0.730812	0.196726	0.072462	1.147827	7.368043	30.31685	0.342041	169.4255	-0.00217	-2.63196	2.616854	0.016854	-0.45796	40.57452
30.625	0.740434	0.192192	0.067375	1.15149	7.24856	30.18777	0.335316	170.9535	0.00149	-2.75144	2.487766	-0.11223	-0.46468	39.04655
30.9375	0.735637	0.194475	0.069888	1.149681	7.308334	30.25189	0.338653	170.1924	-0.00032	-2.69167	2.551892	-0.04811	-0.46135	39.80759

Table 4: Quaternary blend of Western Canada coal (WCAN), UK Ogmore coal (OGM), Lafia-Obi concentrate (LFC) and Okaba coal (as-received) (OKA)

Θ	WCAN	OGM	LFC	OKA	R	A	V	S	C	R1	A1	V1	V2	S1	C1
0	1	0	0	0	1.52	7.2	18.75	0.39	210	0.37	-2.8	-8.95	-11.55	-0.41	
10	0.940587	0.029252	0.029252	0.00091	1.500333	7.483357	19.51908	0.368024	205.6779	0.350333	-2.51664	-8.18092	-10.7809	-0.43198	4.32206
20	0.779677	0.103316	0.103316	0.013691	1.439639	8.246909	21.74666	0.321814	192.9173	0.289639	-1.75309	-5.95334	-8.55334	-0.47819	17.0827
30	0.562412	0.187529	0.187529	0.062529	1.334951	9.266035	25.19716	0.29887	172.4576	0.184951	-0.73396	-2.50284	-5.10284	-0.50113	37.5424
40	0.344258	0.242477	0.242477	0.170788	1.187195	10.26712	29.49204	0.347382	145.8578	0.037195	0.267123	1.792045	-0.80796	-0.45262	64.1422
35	0.450155	0.220781	0.220781	0.108283	1.266085	9.784905	27.26766	0.311945	159.7879	0.116085	-0.21509	-0.43234	-3.03234	-0.48805	50.2121
37.5	0.396053	0.233274	0.233274	0.137398	1.22781	10.03232	28.36456	0.326698	152.9594	0.07781	0.032322	0.664564	-1.93544	-0.4733	57.0406
36.25	0.422857	0.227418	0.227418	0.122308	1.247253	9.909992	27.81178	0.318596	156.4106	0.097253	-0.09001	0.111784	-2.48822	-0.4814	53.5894
36.875	0.409388	0.230446	0.230446	0.129719	1.237606	9.971527	28.08715	0.322463	154.6939	0.087606	-0.02847	0.387154	-2.21285	-0.47754	55.3061
37.1875	0.402703	0.231886	0.231886	0.133525	1.232727	10.00202	28.22561	0.324535	153.8288	0.082727	0.00202	0.525612	-2.07439	-0.47547	56.1712
37.03125	0.406041	0.231172	0.231172	0.131614	1.235171	9.986797	28.15632	0.323487	154.2619	0.085171	-0.0132	0.45632	-2.14368	-0.47651	55.7381
37.10938	0.404371	0.231531	0.231531	0.132567	1.23395	9.994415	28.19095	0.324008	154.0455	0.08395	-0.00559	0.490951	-2.10905	-0.47599	55.9545
37.14844	0.403537	0.231709	0.231709	0.133046	1.233339	9.998219	28.20828	0.324271	153.9372	0.083339	-0.00178	0.508278	-2.09172	-0.47573	56.0628
37.16797	0.40312	0.231797	0.231797	0.133285	1.233033	10.00012	28.21694	0.324402	153.883	0.083033	0.00012	0.516944	-2.08306	-0.4756	56.1170