

**STUDIES ON BLEND DESIGN FOR ENHANCING
COKEABILITY OF LAMZA COAL**

BY

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SEPTEMBER, 2004.

CERTIFICATION

This work has not been presented elsewhere for the award of a degree, or any other purpose.

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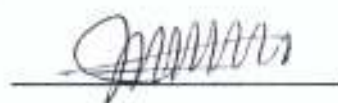
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This project is dedicated to God; the Almighty, Who is the Source of all wisdom and knowledge, and to the loving memory of my late mother, Mrs. Asunke Adeleke, who laboured tirelessly for my upbringing and education.



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ABSTRACT

The bituminous prime coking coal with plastic properties suitable for metallurgical cokemaking constitutes only about 5% of the world's known coal reserve. In Nigeria, Lafia coal with intolerable ash and sulphur content of 25.60% and 2.30% respectively, is the only medium coking coal known before now. Further exploration efforts to find a higher grade local coal led to the location of Lamza coal in Adamawa state. In this work, proximate analysis, Gieseler fluidity, and Ruhr dilatation tests were conducted on Lamza coal and its blends with Ondo bitumen. From the results obtained, theoretical blend formulations to obtain cokeable coal blends was carried out between Lamza coal, Ondo bitumen and some prime coking foreign coals.

The results obtained showed that addition of 15% bitumen upgraded Lamza coal from the weakly caking International Standards Organization (ISO) grade 811 to the medium coking ISO grade 812, with G-value of 0.971. Additionally, the Ruhr dilatation was raised by 18% and the Gieseler fluidity by 223 ddpm. Blend design calculations also showed that up to 44.44% of Lamza coal can produce a cokeable blend with 11.53% Lafia coal and 44.03% prime coking Canadian coal; translating to a saving of about N5.53 billion on Ajaokuta Steel Plant 1.3 million tons proposed annual import of coking coal. When the results obtained are upgraded on pilot scale, the critical problem of producing affordable blast furnace coke for sustainable iron and steelmaking when Ajaokuta Steel Plant starts operation would have been solved.

CHAPTER ONE: INTRODUCTION

1.1 COAL AND ITS ORIGIN

Coal is a solid combustible rock. It consists of a complex mixture of organic chemical substances containing carbon, hydrogen and sulphur. It is a fossil fuel formed chiefly by the action of temperature and pressure on plant debris over several million of years (Francis et al, 1980). Coals are classified as - lignite, sub-bituminous, bituminous and anthracite - depending on their degree of coalification. Although coal may originate from isolated fragments of a variety of vegetation, most coal represents the coalification of woody plants accumulated in peat beds. Biochemical activity modifies the character of the un-submerged, lightly submerged, or lightly buried peat. This process consists partly of general oxidation, but mainly of attack by aerobic bacteria and fungi, which can live only where oxygen is available, and of anaerobic bacteria where water or thin sediments cover the peat.

1.2. CLASSIFICATION OF COALS FOR COKEMAKING

The classification and description of coal depend mainly upon information obtained by chemical analysis. There are two kinds of chemical analysis: the ultimate analysis and the proximate analysis. The ultimate analysis refers to determination for percent hydrogen, carbon, oxygen, nitrogen, and sulphur, excluding ash. The proximate analysis involves determination for volatile matter, fixed carbon, moisture and ash. Calorific and sulphur content values are also determined. Qualifying terms such as - as determined (ad), dried basis (db) and dried ash free basis (daf) are

commonly used to denote the basis of the reported analysis. Mineral matter is the inorganic material present in coal that forms ash when coal is burned. It occurs mainly as discrete mineral phases, and also as chemical elements combined with organic matter and as dissolved elements in the pore water. Pyrite, quartz, calcite and various types of clay minerals are the major components of mineral matter in coals..

The term rank refers to the stage of coalification reached by a coal in the course of metamorphism. Coal classification by rank is fundamental in coal characterisation and is generally based upon chemical composition and petrographic analysis. Petrographic analysis gives a precise definition of a coal's rank using coal's vitrinite reflectance. Table 1 shows the International Standards Organisation (ISO) coal classification chart. In the American Society for Testing and Materials (ASTM) method, coals are classified by rank in ascending order as lignite, sub-bituminous, bituminous and anthracite (McGraw-Hill Encyclopedia,1987) . In petrographic concept, a coal is a rock substance composed of banded ingredients called lithotypes-vitrain, clarain, durain, and fusain - and also mineral matter. Macerals are the individual components of lithotypes and are comparable to minerals composing most rocks. Macerals are recognised by their optical properties and morphology.

They differ from minerals in that macerals possess no fixed chemical composition or crystal structure such as those of minerals. Each maceral becomes progressively modified chemically and physically, as the rank of the coal advances. Hence, the common practice now is to indicate the rank position of individual macerals solely by using some physical attribute, power of reflectance being the most widely used because of its relative simplicity. In order to distinguish the different macerals under the microscope, parameters such as reflectance and colour are used (Gebruder, 1975). Lignites are immature coals that are intermediate in composition between peat and bituminous coals. Anthracite is the most mature form of coal with very high carbon content. Of primary concern however are the bituminous coals, which are carbonized to produce metallurgical grade coke for use in the blast furnace. Unfortunately, high grade bituminous coals are scarce worldwide accounting for only about 5% of the world supply of coals (Bujnowska et al, 1992).

1.3 THE PLASTIC PROPERTIES OF COALS

The fraction of a coal soluble in benzene and chloroform is termed the "coking principle" and is called bitumen. Pyrolysis transforms coal into fluid products either completely or partially. It is the appearance of these fluid products which causes softening and plasticity. The disappearance of the fluid products either by evaporation or thermal decomposition leads to resolidification. These fluid products are called thermobitumens. It is postulated that thermobitumens forms the primary pyrolytic product, mainly

primary tars and a little gas. At the temperature at which they form, the vapor pressure of these tars is low, so that they remain for sometime in the liquid state, dispersed in the coal thus making it plastic. Subsequently, they disappear either by evaporation or by thermal decomposition giving off gas or vapor and leaving behind a solid residue which aggregates to form a semi-coke. In low rank coals, thermobitumens are abundant but have little thermostability - decomposing rapidly so that their concentration is always low (Lowry, 1963).

Dilatometers and plastometers are commonly used to study coal's plastic properties for cokemaking. Coal quality is now being predicted with considerable accuracy from the dilatation characteristics of the constituent of the blend. Mathematical expressions had been developed to predict cokeability from plastic behaviour parameters. The coking capacity, G, for example is defined by Simonis' relation from dilatometer analysis results (Skerl, 1988; Price et al, 1987; Afonja, 1991):

$$G = \frac{E + V}{2} \times \frac{c + d}{V \times c + E \times d} \quad 1.1$$

where:

- G = Coking capacity
- E = Softening temperature
- V = Temperature of maximum dilatation
- c = % maximum contraction
- d = % maximum dilatation

Coals with G - values ranging from 0.95 - 1.10 are expected to produce metallurgical grade coke on carbonisation. Fig.1 shows the typical Simonis' dilatation curve with associated parameters.

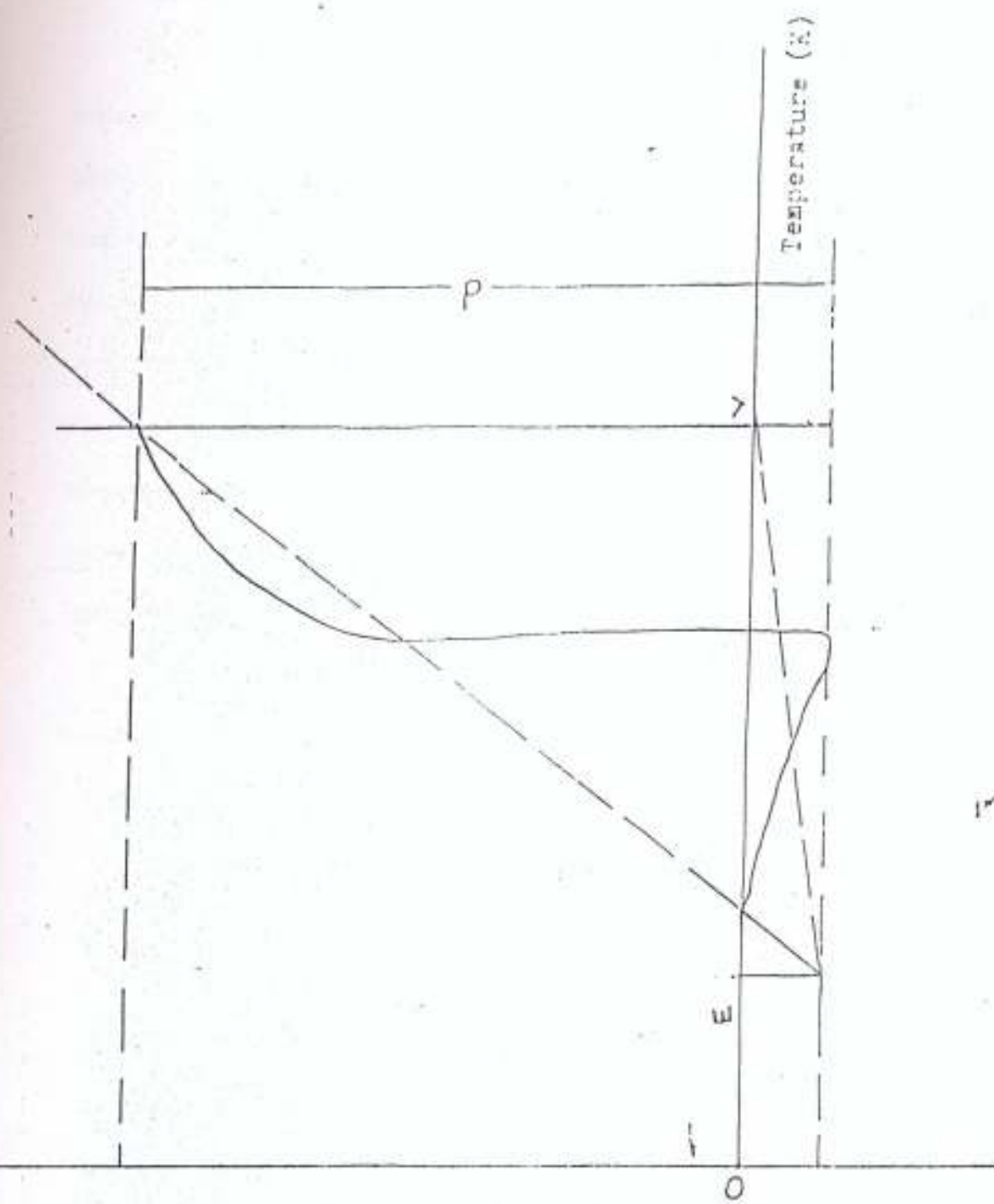


Fig.1: Simonis' Dilatation curve (Afonja, 1991)

1.4 COKING ADDITIVES FOR PLASTIC PROPERTIES

IMPROVEMENT

Research work over the years had proved that coals' plastic properties are commonly improved by using bitumen, pitch and coal tar as coking additives (Bujnowska, 1992; Dumitrescu et al, 1987). Bitumen is the generic term for mixtures of natural and pyrogenic hydrocarbons, particularly heavy hydrocarbons such as wax, pitch and asphalt. It consists almost entirely of carbon and hydrogen with very little oxygen, nitrogen and sulphur. It is soluble in carbon tetrachloride, benzene or carbon disulfide. Asphalt is a natural or mechanical mixture of solid or viscous bitumen with inert mineral matter (Bennett, 1962). Chemical properties of Ondo bitumen is shown in Table 2.

Table 2: Chemical Properties Of Bitumen (BPIC Office, Akure).

S/NO	Chemical Properties %	Value
1.	Saturates	22 – 24
2.	Aromatics	12 – 19
3.	Resins	39 – 44
4.	Asphaltene	9 – 18
5.	Sulphur	1.3

Saturates are compounds in which all of the valence bonds of the elements are satisfied. In organic chemistry, this refers to compounds having no double or triple bonds. Aromatics are organic compounds containing one or more benzene rings. Resins are semi-solid or solid, complex, amorphous mixture of organic compounds. Asphaltene refers to the component of

bitumens which is soluble in carbon tetrachloride or carbon disulphide, but insoluble in petroleum ether (Bennett, 1962). Thermal cracking of bitumen produces coke, asphaltenes, resins, aromatics, saturates and gases. The large molecules are converted to smaller ones that can be used in distillate fuels and sulphur, nitrogen and metal contents are reduced to acceptable level during upgrading of bitumen (Refa, 1988). The viscosity of bitumen had been shown to depend on its asphaltene concentration (Robert et al, 1984). Coal tar constitutes the major part of the liquid condensate obtained from the carbonisation of coal. Coal tar is processed to produce phenols, cresols, anthracene, naphtha and pitch. Pitch is a black, shiny residue from the processing of coal tar. Pitch is solid and brittle at low temperatures and liquid at high temperatures (Considine, 1974).

Nigeria is blessed with a notable deposit of natural bitumen, which is reported to be the second largest in the world. The natural bitumen deposits in Nigeria are located within a belt ranging from East of Ijebu-Ode through Okitipupa and Odigbo areas of Ondo state to the Western margin of Edo/Delta states (Owolabi, 1997)). The bitumen used in this work was obtained from Gbeleju Loda village in Irele Local Government area of Ondo State.

1.5 THE NIGERIAN COAL DEPOSITS

Coke ability is a measure of a coal caking and coking ability. Accordingly,

four combinations of coal properties are possible:

- (i) Strongly caking, strongly coking
- (ii) Strongly caking, medium coking

- (iii) Weakly caking, weakly coking
- (iv) Non-caking, non-coking.

Coals of category (iv) are non-caking and cannot be made cokeable under any known condition, while coals of category 1 produce metallurgical grade coke on straight carbonization. Cokeability improvement and co-carbonization with coking additives are only applicable to coals of categories (ii) and (iii). Unfortunately, tests conducted over the years on known local coals (estimated to be about 1.5 billion tons in reserves), showed that most of them belong to category 4 of coals. Table 3 shows the status of known Nigerian coals (Task Force, 1987).

Table 3: Status Of Nigerian Coals (Task Force, 1987)

Coal Location	Proven Reserves (millions tons)	Inferred Reserves (millions tons)	Cokeability
Enugu	54	250	non-caking
Okaba	74	250	non-caking
Ogboyoga	107	320	non-caking
Lafia-Obi	22	Unknown	Strongly caking, medium coking.

Lafia – Obi coal is the only Nigerian coal with good coking properties, but with high ash and high sulphur. It has been extensively explored with 137 boreholes and 2 shafts made. Out of 36 seams identified, only seams No 12 and 13 are possible for mining. Consequently, out of 22 million tons of proven reserves, only 15 million tons are workable and 6.42 million tons recoverable. The area is geologically disturbed, with heavy faulting, normal and reversed, with throws ranging from 8m to 125m. Because of the difficulty of the mining

conditions, mining will have to be fully or semi-mechanised with delivery cost per ton of N87.50 or N93.80, respectively (Task Force, 1987; This Day Newspaper, 2003).

The Benue trough of Nigeria is a sedimentary basin extending from the Gulf of Guinea in the Southwest to the Chad Basin in the Northeast and it is geographically sub-divided into a lower, middle and upper portions. The Lafia Obi coal is in the middle portion of the trough while Lamza coal is in the upper portion (Obaje et al, 1999; Peskett, 1999). In its efforts to find another local coking coal deposit, the National Steel Raw Materials Exploration Agency (NSRMEA), Kaduna, later found the Lamza coal deposit in Guyuk local government of Adamawa state. NSRMEA recently sent three samples of this deposit to the National Metallurgical Development Centre (NMDC), Jos, for testing and cokeability evaluation. Since Lamza coal is in close proximity of Lafia coal and in the same Benue trough, it may have a similar origin to Lafia coal. The reserve is likely to be significant since it appears on Nigerian Coal Corporation geological map of local coals (Fig.2).

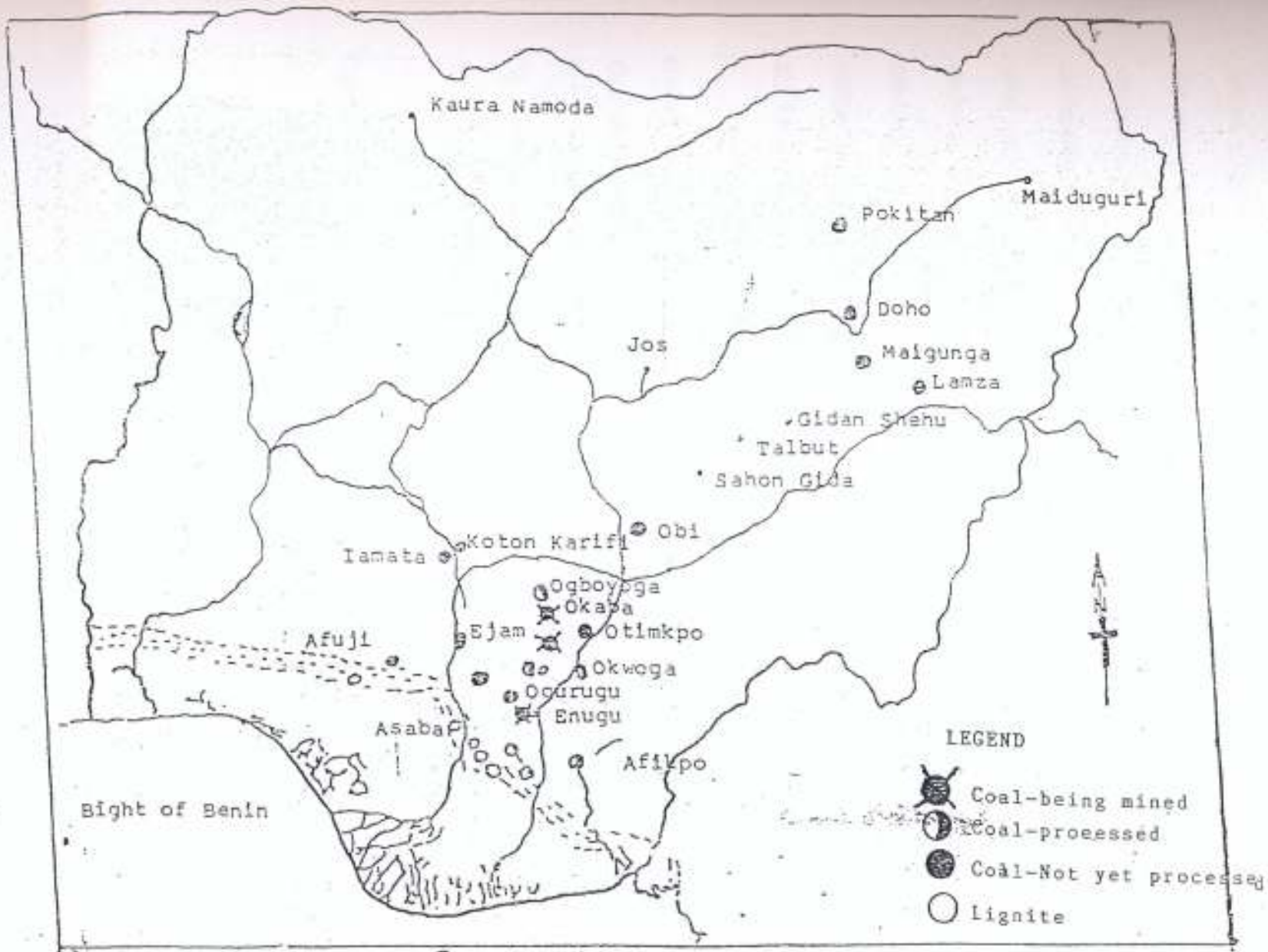


FIG. 2 : COAL/LIGNITE OCCURRENCES IN NIGERIA (Peskett, 1999)

1.6 COKEMAKING AND COKE PROPERTIES

The cokemaking process involves carbonisation of coal at high temperatures (about 1,100°C) in an oxygen deficient atmosphere in order to concentrate the carbon. The industrial cokemaking process can be sub-divided into two categories – by-product cokemaking and non-recovery/heat recovery cokemaking. A good quality coke is generally produced from carbonisation of good quality coking coals. In the blast furnace, coke fulfils certain essential chemical, thermal and physical roles. It serves as a reducing agent and provides the heat required for the reduction process and slagging. Additionally, coke physically supports the overlying burden and provides gas and liquid permeability (Kim, 1998).

For the Ajaokuta Steel Plant, the coal blend for cokemaking and coke characteristics required are as follows (Raw Materials Specifications, 1994):

Coal blend characteristics:

- (i) Total moisture - 5 - 9%
- (ii) Volatile matter (daf) - 27.7 - 30.3%
- (iii) Ash - 10% maximum
- (iv) Sulphur – 0.9% maximum

Coke characteristics:

- (i) Coke output (run of oven) - 735 - 770 kg/ton
- (ii) ISO Micum 40 - 78% minimum
ISO Micum 10 - 9% maximum
- (iii) Coke ash content - 13% maximum



1.7 OBJECTIVES OF THE RESEARCH

On completion of its first phase, the Ajaokuta steel plant (ASP) will require about 1.3 million tons of coking coal to produce coke to smelt iron in its blast furnace for an output of 1.3 million tons of steel annually (Task Force, 1987). At a cost of \$100 per ton (Pesckett, 1999), ASP will need about \$130 million (that is, about N20 billion) to import coking coals annually. Considering this huge amount to import a single input for ironmaking, there is an urgent need to explore for new coal deposits and test them to determine their suitability as possible components of blends with foreign coking coals to produce coke at Ajaokuta. This work is therefore aimed at improving the cokeability of the low grade Lamza coal using bitumen from Ondo state.

The objectives of this research work encompass the following:

- (i) Characterisation of Lamza coal and its classification in accordance with the International Standards Organisation (ISO) code
- (ii) Conduct of laboratory scale blending tests on weakly coking Lamza and medium coking Australian coals using Ondo bitumen as a coking additive
- (iii) Analysis of Lamza coal ash for its oxide composition and prediction of its behaviour on the blast furnace operating efficiency.
- (iv) Development of theoretical coal blend formulations between Lamza coal and some foreign prime coking coals.

The scope of this research work was limited by the following constraints:

- (i) The extent of the tests conducted was limited by the quantity of samples received. Consequently, only the bench scale tests for cakeability and cokeability evaluations were conducted. Additionally, it was rather difficult to obtain prime coking coals to conduct actual blend formulation tests.
- (ii) Non-availability of a photometer to conduct qualitative and quantitative petrographic analysis of Lamza coal to determine its precise rank in terms of average vitrinite reflectance. Therefore, the values of average vitrinite reflectances of the coals for which blend formulation studies were done are only estimates from a standard curve of vitrinite reflectance versus volatile matter content (Panaitescu, 1992).
- (iii) The current delivery cost estimate per ton of Lafia coal for full or semi-mechanised mining is not known. Considering the great devaluation of the Naira since 1977 when the first estimate was made, a delivery cost of \$87.50 per ton is assumed in blend formulation studies instead of ₦87.50 that was then estimated.

CHAPTER TWO: LITERATURE REVIEW

2.1 PLASTIC BEHAVIOUR OF COALS

During coke formation, the solid particles of coking coal on heating first release water and absorbed gases and then become plastic, swell and agglomerate. In this plastic state, some decomposition occurs in the coal and the gaseous products liberated within the plastic mass cause the swelling of the coal (Moitra et al, 1972). The course of the plasticity phenomenon during coal carbonisation depends on the quantity and nature of bitumens content and that of humic substances of the coal blend (Roga, 1958). During carbonisation, the maceral vitrinite depolymerises causing the formation of a liquid mass in the coal. This is followed by the condensation reaction to produce coke- aromatic rings of vitrinite condensing to high molecular weight residue. Plastic dilatation behaviour generally increases with increasing H/O ratio, while high inertinite content and low H/O ratio reduces the swelling tendency of the coal. Ratio of hydrogen in the aromatic and non-aromatic parts of vitrinite macromolecule influences the caking and coking properties (Kosina, 1983).

2.2 EFFECTS OF COKING ADDITIVES ON PLASTIC PROPERTIES OF COALS

Research work had been done jointly by Ruhrkohle AG and Bergbau-Forschung GmbH into the effect of the addition of carbon or oil derivative pitches and bitumens on the quality of coke. The research studies proved that the use of these coking additives effectively improved the carbonization properties of poorly coking coals. The results showed that addition of 7%

carbon pitch to a poor coal will produce the same improvement in coking property that addition of 50% coking coal will do. Addition of 8% bitumen to a German coal blend raised its G-value coking capacity to 0.973 and thus produced a coke with good strength properties (Weskamp et al, 1987).

The role of mobile hydrogen in coal pitch co-carbonisation with high volatile coals had also been investigated. The ability of coal pitch to improve cokeability was found to depend on its ability to donate hydrogen to coal. The extent of cokeability improvement obtained was found to vary with the properties of pitch and coal. A coal with over 70% inertinite could not have its coking properties modified with coal-tar pitch (Feng et al, 1987). Metallurgical coke production in Romania also involves the use of significant amounts of low grade coals which necessitates co-carbonisation with coal-tar pitch to improve the coking properties. Semi-industrial co-carbonisation studies with non-coking coals and coal-tar pitch showed improvement in the quality of coke produced (Dumitrescu et al, 1987).

Co-carbonisation of coals with coal-tar pitch as a coking additive to produce foundry coke is being practiced in China. Coal-tar pitch serves as a binder and also modifies the coals coking ability effectively (Qian et al, 1992). Another study in India (Zhu, 1987) also showed that coal-tar addition to fat coal improves fluidity and mesophase development during pyrolysis. Co-carbonisation of low grade coals and coal-tar pitch had also been done in Poland (Bujnowska et al, 1992).

The results obtained showed that medium and weakly coking Polish coals required addition of 5% and 10% coal tar pitch, respectively, to improve their plastic properties for metallurgical cokemaking.

2.3 COAL RESEARCH IN NIGERIA

Research work on coking behaviour of Nigerian coals was initiated at Ife in 1970. Coal samples from local deposits such as Enugu, Okaba and Lafia had been studied. Enugu and Okaba coals were found to be sub-bituminous with poor thermoplastic properties. Only Lafia coal is bituminous but with high sulphur and high ash contents. Coal blending studies were also conducted. The studies showed that only about 1 to 2 percent of Enugu and Okaba coals can be incorporated into a blend with a prime coking coal. Laboratory scale tests also showed that up to 30 percent of low temperature char from Enugu or Okaba may be blended with a high fluidity coal to produce metallurgical coke. Studies at Ife also showed that formed coke can be produced from Enugu coal using its coal-tar pitch as a binder (Afonja, 1991). Blend formulations involving the prime coking United Kingdom Ogmores coal, Enugu coal, Lafia coal and Ashland petroleum pitch as a coking additive had also been successfully done on laboratory scale in United Kingdom (Ndaji et al, 1987).

2.4 EFFECTS OF COAL ASH COMPOSITION ON COKE BEHAVIOUR IN THE BLAST FURNACE

The effects of coal ash composition on the performance of coke in the blast furnace had also been investigated. In his work, Forsberg found that potassium oxide catalyses the solution loss reaction (around 900 - 1000°C) of

coke thus weakening it and increasing its reactivity in the blast furnace. This lowers the shaft efficiency of the blast furnace (Forsberg, 1987). In another work, it was found that potassium causes a marked increase in coke's bulk reactivity. While potassium's critical threshold level to cause weakening of coke is about 1.5% that of sodium is in excess of 4% (Tucker et al, 1987). In their work, Helleisem et al (1987), found that potassium oxide decreases the gasification threshold temperature from the classical figure of 950°C to 750°C - 850°C, depending on the amount of potassium oxide and the nature of the coke. Alkali oxide content of coke is usually restricted to less than 0.25% (Barsotti et al, 1987). Table 4 shows the SiO_2 : Al_2O_3 ratios for some Canadian coal blends.

It has also been found that alkali carbonates deposited on coke at 800 - 850°C increase coke reactivity but do not affect coke size or strength. Alkali metal vapour also reacts with coke carbon at 1100 - 1450°C reducing the abrasion resistance of the coke and making it very susceptible to size reduction by mechanical action. This is a major factor and can produce 15 -20 mm of coke size reduction (Willmers et al, 1992).

Table 4: $\text{SiO}_2 : \text{Al}_2\text{O}_3$ Ratio Of Coals For Cokemaking (Price et al, 1987)

Coals/Blends	$\text{SiO}_2 : \text{Al}_2\text{O}_3$ ratio
Bulli coal	1.4
Western Canada blend A	2.07
Western Canada blend B	1.96
Western Canada blend C	2.11
Appalachian blend A	1.74
<i>Appalachian blend B</i>	1.63
Appalachian blend C	1.53
Appalachian blend D	1.56

2.5 ANALYSIS RESULTS ON BULLI COKING COAL

The results of typical quality analysis tests conducted on the prime coking Australian Bulli coal are shown in Tables 5 to 10 (BHP Publication, 1998).

Table 5: Proximate Analysis Of Bulli Coal.

	As received	Air Dried	Dry	Dry ash Free
Total Moisture (%)	8.5	(8.5)	(8.5)	(8.5)
As analyzed moisture (%)	(1.0)	1.0	(1.0)	(1.0)
Ash (%)	8.8	9.5	9.6	(9.6)
Volatile Matter (%)	-	21-22	-	-
Total Sulphur (%)	0.35	0.38	0.38	0.42

Table 6: Carbonization properties of Bulli coal.

Parameters	As Analyzed
Crucible Swelling Number	6.5
Gray-King Coke Type	G3
Audibert- Arnu Dilatometer	
Maximum Contraction (%)	25
Maximum Dilatation (%)	20
Initial Softening Temp. (°C)	400
Maximum Contraction Temp. (°C)	450
Maximum dilatation Temp. (°C)	480
Gieseler Plastometer	
Maximum Fluidity (ddpm)	1000-1500
Initial Softening temp. (°C)	410
Maximum Fluidity temp. (°C)	460
Solidification temp. (°C)	495
Plastic Range (°C)	85

Table 7: Ultimate analysis of Bulli coal.

	Dry Ash Free
Carbon (%)	88.6
Hydrogen (%)	4.9
Nitrogen (%)	1.6
Oxygen (%)	4.5
Sulphur (%)	0.4

Table 8: Ash analysis of Bulli coal.

Parameters	Dry
SiO ₂ (%)	52
Al ₂ O ₃ (%)	36
CaO (%)	1.8
K ₂ O (%)	1.20
Na ₂ O (%)	0.38
SiO ₂ :Al ₂ O ₃ ratio	1.4

Table 9: Petrographic analysis of Bulli coal.

Parameters	As Analyzed
Reflectance (Ro max)	1.28
Macerals (mmf)	
Vitrinite (%)	50
Exinite (%)	0
Semi-Inertinite (%)	15
Inertinite (%)	35

Table 10: Micum indices of coke from Bulli coal.

Micum M40	82
Micum M10	8

Bulli coal is a hard coking coal capable of producing a metallurgical grade coke of high strength and ideal reactivity. It is a self-coking coal of medium volatile matter content and it can be blended with cheaper quality coals in the cokemaking process. The relationship between average vitrinite

reflectance and coke strength micum indices for coke produced from Indian coals is shown in Table 11 (Singh et al, 1987).

Table 11: Coke strength of Indian coke (Singh et al, 1987).

Blends	Average reflectance of Vitrinite	Top charging	
		M10	M40
Blend 1	1.22	10.0	81.8
Blend 2	1.14	11.0	79.8
Blend 3	1.04	11.4	82.2
Blend 4	1.12	11.3	78.2
Blend 5	1.15	10.4	81.0

2.6 MATHEMATICAL MODELS FOR COKEMAKING

Mathematical models have been developed to facilitate coal blending for cokemaking. A model to simultaneously optimize coal blends for five coke plants while satisfying coke requirements at minimum cost was developed at LTV Steel Company Ohio, United States. A linear programming model was used and the constraints employed include coke stability, ash and sulphur contents. The model predicts coke strength on the basis of average vitrinite reflectance (Skerl, 1988). Regression equations had also been developed to relate coke strength (M10 and M40 indices) to coal blend parameters of average vitrinite reflectance, percentage of inert macerals and the so-called capacity for inerts (Shiyong, 1987).

2.7 JUSTIFICATION OF RESEARCH WORK

This literature survey had shown that extensive studies on cokeability improvement of coals using coking additives had been conducted over the years. However, cokeability improvement studies on Lamza coal using Ondo bitumen as a coking additive had not been reported in literature. Therefore, the present research work can be justified on the following ground:

First – Thus far, all the known local coals are unsuitable for straight carbonisation and are not blendable with prime coking coals appreciably. While Enugu and Okaba coals are non-caking, Lafia coal - which is medium coking has intolerable content of ash and sulphur and its mineability economically is in doubt. This situation informs the present efforts to determine the cokeability of Lamza coal.

Second - Bituminous additives such as bitumen had been successfully co-carbonized elsewhere with different grades of coals with positive effects on cokeability. The use of locally sourced bitumen as a coking additive has not been reported in literature.

Third - On completion of its first phase, Ajaokuta Steel Plant is expected to import 1.3 million tons of prime coking coal per annum to produce its blast furnace coke. At a cost of only \$100 per ton, a sum of \$130 million will be needed (Peskest, 1999). A blending design incorporating only 10% of local coals and coking additive will save about ₦2.0 billion in foreign exchange as at July, 2004.

CHAPTER THREE: RESEARCH METHODOLOGY

3.1 MATERIALS

The materials used in this work include:

1 kg each of three sets of coal samples were obtained from Lamza, Adamawa state, Nigeria.

1 kg of Australian coal sample was obtained from the Minerals laboratory of the National Metallurgical Development Centre (NMDC), Jos, Nigeria.

10 kg of bitumen from Gbeleju Loda area of Ondo state, Nigeria, in semi-solid form.

Chemical reagents used are benzene, chloroform, hydrochloric acid, sulphuric acid, hydrogen fluoride, sodium carbonate, magnesium oxide, sodium hydroxide, EDTA solution, nitric acid, hypochloric acid, magnesium chloride, potassium hydroxide and barium chloride.

3.2 EXPERIMENTAL

All the experiments were conducted at the National Metallurgical Development Centre (NMDC), Jos, with the exception of the determination for calorific value that was done at the Fishery department, Federal University of Technology, Akure. The air-dried coal sample was ground in the iron mortar and test samples were obtained by passing the pulverised coal through sieves of required mesh. The experiments conducted include proximate analysis to determine chemical composition parameters such as moisture, ash, volatile matter and fixed carbon. Technological tests for coal's plastic properties such as free swelling index to assess cakeability, Gieseler plastometry to determine fluidity behavior and Ruhr dilatometry to evaluate contraction and dilatation

behaviour were also carried out. The sulphur content, calorific value and ash composition analysis were also conducted as described below.

3.2.1 PROXIMATE ANALYSIS

Proximate analysis of coal and coke involves the determination of moisture content, volatile matter content, ash content and fixed carbon of coal and coke.

Determination of Moisture Content

The crucible was preheated at a temperature of 110°C for 1 hour. 1 g of coal ground to pass 250 microns was then heated in the crucible at 110°C for 1 hour. The loss in weight accounts for the moisture content.

Determination of Volatile Matter (VM)

The silica crucible was pre-heated in the muffle furnace for 7 minutes at 900°C and cooled. 1g of sample ground to pass 250 microns was then placed in the crucible and heated in the muffle furnace for 7 minutes at 900°C . The loss in weight accounts for the volatile matter of the coal or coke sample.

Ash Content Determination

The silica crucible was pre-heated in a muffle furnace at 825°C for 1 hour. It was then cooled and weighed. 1g of sample ground to pass 250 microns was then placed in the crucible and heated in the muffle furnace at 825°C for 1

hour with the lid on. It was then cooled in the desiccator and weighed. The incombustible residue constitutes the ash content.

Fixed Carbon Determination

Fixed carbon of coal or coke was determined by calculation with the relation:

$$\% \text{ Fixed carbon} = 100 - \% \text{ moisture} - \% \text{ Ash} - \% \text{ VM.} \quad 3.1$$

The results of proximate analysis are shown in Table 12.

3.2.2 FREE SWELLING INDEX

1g of coal sample, ground to pass 250 micron was heated on Bunsen flame for 7 minutes. The coke button obtained was then compared with standard profiles and the appropriate number determined. Standard FSI profiles are shown in Fig.3. The results of crucible swelling tests are shown in Table 12.

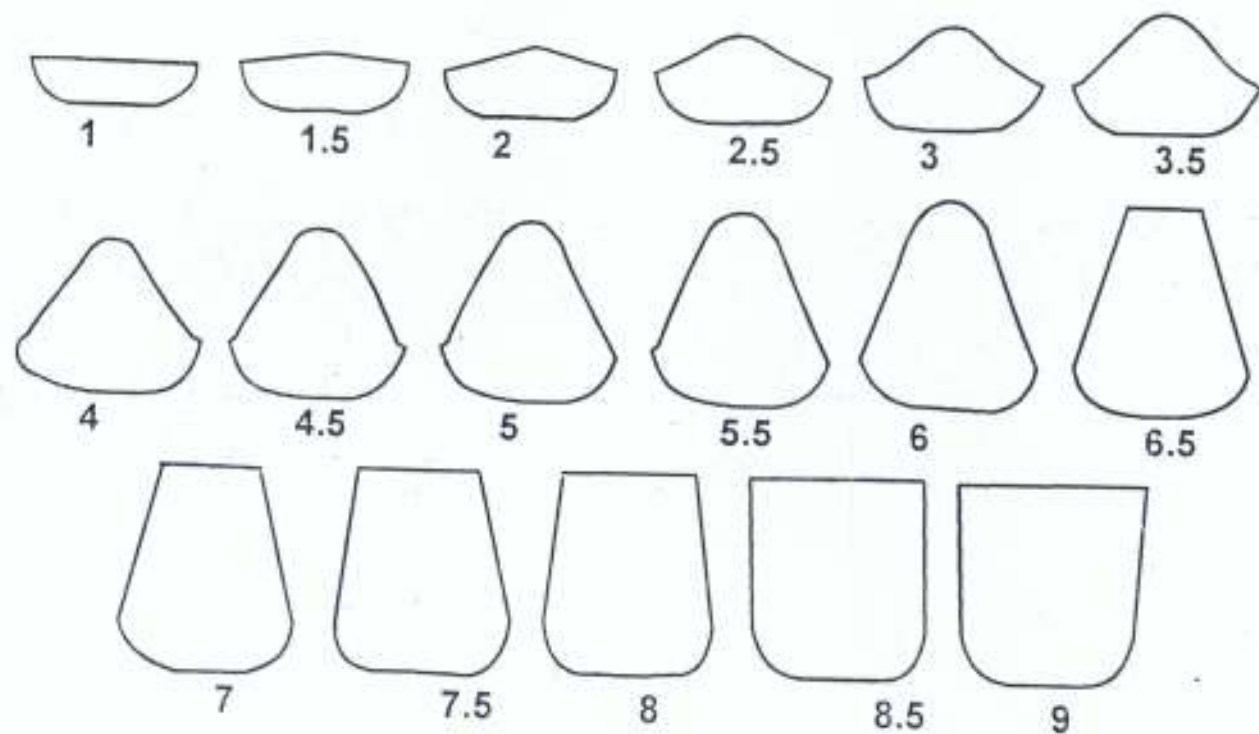


FIG. 3: STANDARD FSI PROFILES

3.2.3 GIESELER PLASTOMETRY

Gieseler plastometer consists essentially of a cylindrical capsule of approximately 21.4mm in diameter and 18.3mm in height. It has a stirrer which has one end tapered to a point for resting in a groove at the center of the capsule for frictionless rotation. Four rabble arms are fitted at right angles to the tapered end of the stirrer such that these wholly lie inside the capsule when the apparatus is assembled. The other end of the stirrer is coupled to an electric motor to provide a constant torque to the axis of the stirrer. The speed of rotation is displayed on the printer console.

5g of the coal sample ground to pass 425 micron was compressed by a 10kg weight placed on the sample with the stirrer arms fully embedded. After assembling the apparatus, the 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 started when the coal softened and continued as long as the coal remained in the plastic state. The movement stopped when the coal re-solidified. The speed of rotation (in dial divisions per minute (DDPM)) varies with the fluidity of coals. The results of Gieseler plastometry are shown in Tables 13 and 14.

3.2.4 RUHR DILATOMETRY

In Ruhr dilatometric test, the variation in the length of a column of coal during heating is measured. The coal sample (ground to 250 micron) was compacted into a pencil form. The pencil of coal was then placed in a metal

tube and a piston rod was inserted into the tube to rest on piston's 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 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 Ruhr dilatometry are shown in Table 15.

3.2.5 ASH ANALYSIS

Determination of Silica in Ash

0.2g of the ash sample was weighed into a platinum crucible and mixed thoroughly with the fusion mixture ($K_2CO_3 + Na_2CO_3$ 1:1) and then covered up with some of the fusion mixture. It was fused at a temperature of $950^\circ C$ in a muffle furnace and allowed to cool. The fused mass was then extracted into a 400ml beaker using 50ml of 1:1 HCl. The solution was dehydrated on the hot plate using asbestos pad, after which it was cooled and 10ml concentrated HCl was added. Distilled water was used to make up the volume to the 50ml mark in the beaker. It was allowed to boil and filtered through No. 541 filter paper. The residue was washed with 1:4 HCl 3 times and with hot water several times until the residue was free from HCl. The filter paper was folded into the platinum crucible and ignited at a temperature of $950^\circ C$ to constant weight (20 minutes).

It was then cooled in the desiccator and weighed as W₁. About 8 drops of 1:1 H₂SO₄ and 15 ml HF were added to the residue in the crucible. It was then heated in a sand bath placed on a hot plate to ensure slow evaporation. At the end, copious fumes were observed leaving the dried mass. The residue was then ignited in a muffle furnace at 950°C for 20 minutes. It was cooled in a desiccator and the crucible weighed as W₂. The percentage silica is calculated with the formula:

$$\%SiO_2 = \frac{(W_1 - W_2) \times 100}{\text{Weight of the sample}} \quad 3.2$$

where: W₁ = Weight of the platinum crucible with the material before hydrofluorisation.

Determination of Alumina in Ash

0.1g of the ash sample was weighed into a nickel crucible. 10 pellets of sodium hydroxide and a pinch of sodium carbonate was added. The mixture was melted over hot plate and finally fused over a low flame at 700°C for 15 minutes. The crucible was set outside and allowed to cool in air. When cooled, the crucible along with the content was dropped in a 250ml beaker and slowly, 100ml of hot distilled water was added and boiled for 10 minutes. The crucible was stirred with a glass rod and washed thoroughly with water into the beaker. The hot solution was filtered through No. 40 filter paper into a 500ml conical flask.

The precipitate was washed with hot water for 6 times to ensure that no sodium aluminate remain trapped in the precipitate. The filtrate was

acidified with hydrochloric acid, and 25ml standard EDTA was also added. The pH was adjusted to 5.5 with ammonium hydroxide and hydrochloric acid and the solution boiled for 15 minutes. The solution was allowed to cool and 25ml acetic acid ammonium acetate buffer solution was added. The pH was checked and adjusted to 5.5, drops of xylene orange indicator was added and a lemon colour developed. Standard zinc acetate was used to titrate the solution. The colour changed from lemon yellow to purple indicating the end point. From the titre value, the Al_2O_3 percentage was calculated.

Determination of calcium oxide

0.2g of the sample was weighed into a 25ml beaker. 20ml of 1:1 HCl was added and the sample digested on the hot plate. The solution was then filtered into a 250ml volumetric flask using filter paper 541. The filter paper was washed several times with hot water, and the solution was cooled and made up to mark. 25ml of the aliquot was pipetted into a 250ml conical flask and 100ml of distilled water added. 30mg of $MgCl_2$ + 4ml 8M KOH was added to the solution to precipitate the magnesium hydroxide. After two minutes, about 30mg of potassium cyanide and hydroxylamine hydrochloride were added and allowed to dissolve by constant stirring. The 0.01M EDTA was titrated against the solution using calcon indicator until the colour changes from pink to blue. The percentage calcium oxide was calculated with the formula:

$$\%CaO = \frac{\text{Vol of EDTA} \times 0.5608}{\text{Weight of sample}} \quad 3.3$$

Determination of sodium and potassium oxide

0.5g of the sample was weighed into a Teflon beaker, and 10mls of each concentrated HCl, HNO₃, and 5ml of HOCl₃ was added. The mixture was heated on a hot plate in a flame cupboard to incipient dryness. It was allowed to cool, and 10ml of distilled water was added and boiled on the hot plate. The solution was filtered using a 540 filter paper into 100ml volumetric flask. The residue was washed several times with distilled water to ensure thorough washing of the residue. The residue was discarded and the volume of the solution (filtrate) was made up to mark. The emission of the solution was read using 405 flame photometer machine. The concentration of Na and K of the sample was determined from the emission versus concentration graph prepared from Na and K standard at concentrations: 0, 2.5, 5.0, 7.5, and 10g/ml. The results of ash analysis are shown in Table 19.

3.2.6 DETERMINATION OF CALORIFIC VALUE

Calorific value is the heat produced by the combustion of a unit quantity of a fuel under specified conditions. Calorific value was determined using the adiabatic bomb calorimeter. It was determined by burning a weighed sample in oxygen in a calibrated bomb calorimeter under controlled conditions. The calorific value of the sample was computed from temperature observations made before, during and after combustion. The gross calorific value was used to compute the total calorific content of the coal sample. The calorific values determined are presented in Table 12.

3.2.7 DETERMINATION OF TOTAL SULPHUR IN COAL BY THE ESCHKA METHOD

The method involves igniting 1g of coal sample and Eschka mixture (2 parts of magnesium oxide with 1 part anhydrous sodium carbonate). The sulphur is dissolved in water and then precipitated as barium sulphate. The precipitate is then filtered, ashed and weighed. The experimental procedure is as follows: 1g of coal sample was weighed into a 30ml porcelain crucible and mixed with 3g of Eschka mixture. The mixture was again covered with 1g Eschka mixture. The blank and the standard sample 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 coal particles occur.

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 400ml beaker. The insoluble material in the first beaker was thoroughly washed with hot water. After washing in this manner, the solid was transferred to the filter paper and washed 5 times with hot water. The filtrate volume should be about 250ml. The residue was then discarded. 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 and 25ml of potassium sulphate was also added using an 'A' grade

pipette. The sample was now heated to boiling and 10mls of barium chloride solution was slowly added with stirring. The solution was maintained near boiling for 30 minutes and then stood overnight. The solution was then filtered with a No 42 paper and washed well with hot water. The wet filter paper was placed into a crucible and ignited for 15 minutes. The paper was gradually smoked off in the muffle furnace avoiding burning. The temperature was then gradually raised to 800 °C and maintained for 1 hour. The crucible was cooled and barium sulphate weighed. Total sulphur is calculated as follows:

$$\text{Total sulphur \%} = \frac{(A - B)}{C} \times 13.74 \quad 3.4$$

where

A = mass of barium sulphate from sample

B = mass of barium sulphate from blank

C = mass of sample used.

The results of sulphur analysis by Eschka method are shown in Table 12.

3.2.8 BITUMEN SAMPLE TESTING

Washability and solubility tests were conducted on the bitumen samples.

Washability Test

100g of bitumen (with sand admixtures) was washed with hot water several times in a container until the washing water contained no more sand particles.

Solubility Test

1g of washed bitumen was dissolved with 10ml and 20ml respectively of carbon tetrachloride and benzene. The solution was then filtered with a No.42 filter paper. The results of washability and solubility tests are shown in Table 20. Fig. 4 is the summary of the various tests conducted and their interrelationships in evaluating the cokeability of coals for metallurgical cokemaking.



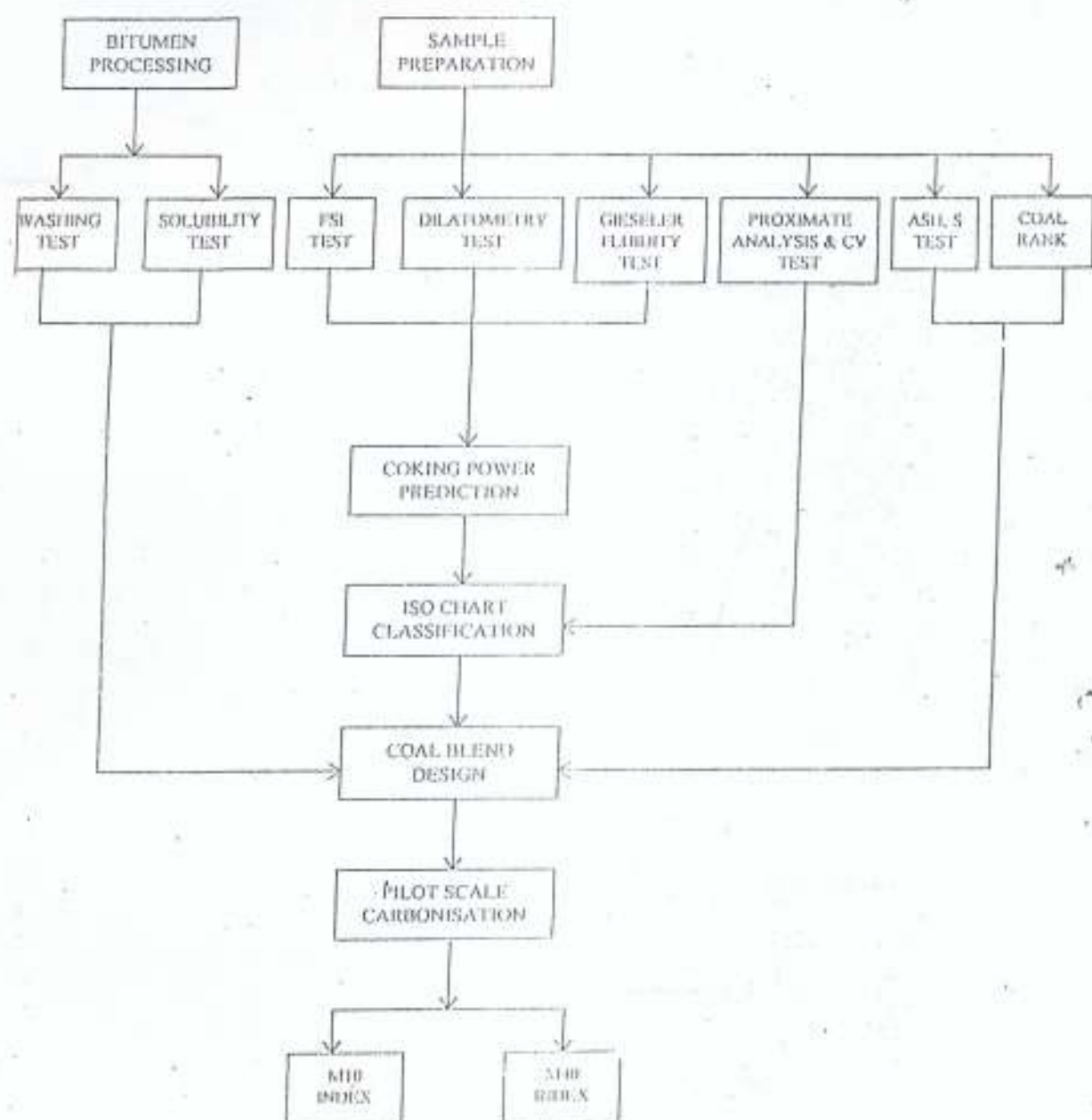


Fig. 4 : SUMMARY OF EXPERIMENTAL METHODS

3.3 BLEND DESIGN

The direct search numerical method was employed to obtain optimum blends of coals that satisfy the various coke strength and chemical composition requirements for metallurgical cokemaking. The coal blending algorithm is shown in Fig. 5. The various search factors – scaling, increment and decrement – were selected for the binary division search iterations in each blending. The convergence criterion for which the iteration terminates was set as $DC < 0.05$ where DC is the maximum error in cost determined for a blend in binary division of interval to find a lower cost. An iteration is successful when it produces a blend that satisfies all the coking requirements of strength and chemical composition with a reduction in cost. The components of the coal blends were calculated using the following mathematical relationships (Adeleke, 1997). For example, the binary blends were calculated as follows:

$$X_1 = \cos^2 \theta \quad 3.5$$

$$X_2 = \sin^2 \theta \quad 3.6$$

For ternary blends

$$X_1 = \cos^2 \theta \quad 3.7$$

$$X_2 = \sin^2 \theta \cos^2 \beta \quad 3.8$$

$$X_3 = \sin^2 \theta \sin^2 \beta \quad 3.9$$

where

X_1 = proportion of coal 1 in the blend

X_2 = proportion of coal 2 in the blend and

X_3 = proportion of coal 3 in the blend

θ and β = angles on the co-ordinate systems that define the blending geometrically.

From the blending tables (tables 23 – 30), the parameters are defined as follows:

R = vitrinite reflectance of coal

A = Ash content

V = volatile matter content

S = sulphur content

C = cost of coals blended per ton

DR, DV, DS, DC = the difference in the vitrinite reflectance, volatile matter, sulphur, cost, respectively calculated and the corresponding standard values of the parameters. The blending algorithm determines the minimum cost for each blend while satisfying the constraints of mechanical strength, sulphur, ash and volatile matter content

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 RESULTS OF ANALYSIS

4.1.1. PROXIMATE ANALYSIS

The proximate analysis of Lamza, Australian, and other local coal samples in terms of moisture, ash, volatile matter and fixed carbon are shown in Table 12.

Table 12: Proximate Analysis, FSI and Calorific Values

Parameters	Lamza 1	Lamza 2	Lamza 3	Lafia Obi Coal	Enugu Coal	Okaba Coal	Australian Coal
Moisture %	1.82	1.63	2.12	1.50	8.15	14.12	1.03
Ash % (db)	7.01	15.51	10.99	26.30	10.42	7.32	5.65
Volatile matter (daf)	42.41	44.12	43.96	32.20	48.90	68.78	30.52
Fixed carbon (daf)	57.59	55.88	56.04	67.80	51.10	31.22	69.48
FSI	1.5	1.5	1.5	6	0	0	2.5
Calorific value kcal/kg	6,593	6,958	6,873	6,045	5,935	5,866	Nr
Sulphur (db)	*0.811	0.831	0.79	2.60	0.73	0.66	0.22

* Determined as average

nr – Not required for ISO classification for coals with volatile matter (daf) < 33%

db – dried basis

daf – dried ash free

4.1.2. FREE SWELLING INDEX (FSI)

The crucible swelling numbers for Lamza coal samples are also shown in Table 12.

4.1.3. GIESELER PLASTOMETRY

Gieseler fluidity characteristics of Lamza and Australian coal samples are shown in Tables 13 and 14.

Table 13: Gieseler Plastometry test (Lamza 1 coal)

Lamza coal + Bitumen	Softening Temp. °C	Resolidification temp. °C	Max.fluidity (ddpm)	Temp. Range °C
L1 + 5% bitumen	No fluidity			
L1 + 8% bitumen	469	479	196	10
L1 + 15% bitumen	457	470	223	13
L1 + 20% bitumen	425	457	838	32

Table 14: Gieseler plastometry test (Australian coal).

Australian coal (L4)+ Bitumen	Softening temp. °C	Resolidification temp. °C	Max fluidity (ddpm)	Temp. Range °C
L4	445	471	2,100	26
L4 + 15% Bitumen	467	483	19,100	16

4.1.4. RUHR DILATOMETRY ANALYSIS

The dilatation characteristics of Lamza and Australian coal pencils are shown in Tables 15 and 16.

Table 15: Dilatation behaviour of Lamza coals.

Coal Blends	Softening Temp. °C	Max. dilatation temp. °C	Max Dilatation %	Max. Contraction %	Absolute Dilatation %
Lamza (L1)	184	-	Nil	- 10	-
Lamza (L2)	186	-	Nil	- 15	-
Lamza (L3)	194	-	Nil	- 10	-
L1 + 10% Bitumen	173	-	Nil	- 8	-
L1+ 15% Bitumen	209	241	0	-18	+18
L2 + 10% Bitumen	178	-	Nil	-10	-
L2 + 15% Bitumen			No Contraction		
L3 + 10% Bitumen	175	-	Nil	-15	-
L3 + 15% Bitumen			No Contraction		

Table 16: Dilatation Behaviour of Australian Coal

Australian Coal + Bitumen	Softening temp. °C	Max. dilatation Temp °C	Max. dilatation %	Max. Contraction %	Absolute Dilatation %
Australian coal (L4)	210	-	-8	-14	6
L4 + 10% bitumen	214	257	28	-8	36
L4 + 15% Bitumen	201	267	10	-13	23

The G-values for the various blends are calculated as shown in the appendix and are presented in Table 17.

Table 17: G-values for coking coals.

Coals and Coal Blends	G-values	Remarks (Price et al, 1987)
Bulli coal	0.994	Coking
Australian coal + 10% Bitumen	1.024	Coking
Australian coal + 15% Bitumen	0.992	Coking
Lamza 1 coal + 15% Bitumen	0.971	Coking

Table 18 shows the relationship of G-values to coke strength in terms of coke stability indices.

Table 18: G-values of coals and relationship to coke strength

Coal and Coal blends	G-value	Coke strength		Remarks (weskamp et al, 1987)
		M10	M40	
Bulli Coal	0.994	8	82	Blast furnace grade coke
German Coal Blend (G1)	0.954	7.8	77.8	Coke
German Coal Blend (G2)	0.973	7.0	78.1	Blast furnace grade coke
Lamza 1 coal + 15% Bitumen	0.971	nd	nd	Blast furnace grade coke predictable
Australian coal + 10% Bitumen	1.024	nd	nd	Blast furnace grade coke predictable
Ajaokuta's Blast furnace coke strength requirements.		≤9.0	≥78	

Note: nd-not determined

The plastic dilatation behaviours of Lamza 1 and Australian coals are shown in

Fig. 6.

Dilatation %

Key:

A- Lamza 1 Coal + 15% bitumen

B- Lamza 1 Coal

C- Australian Coal

D- Australian Coal + 10% bitumen

E- Australian Coal + 15% bitumen

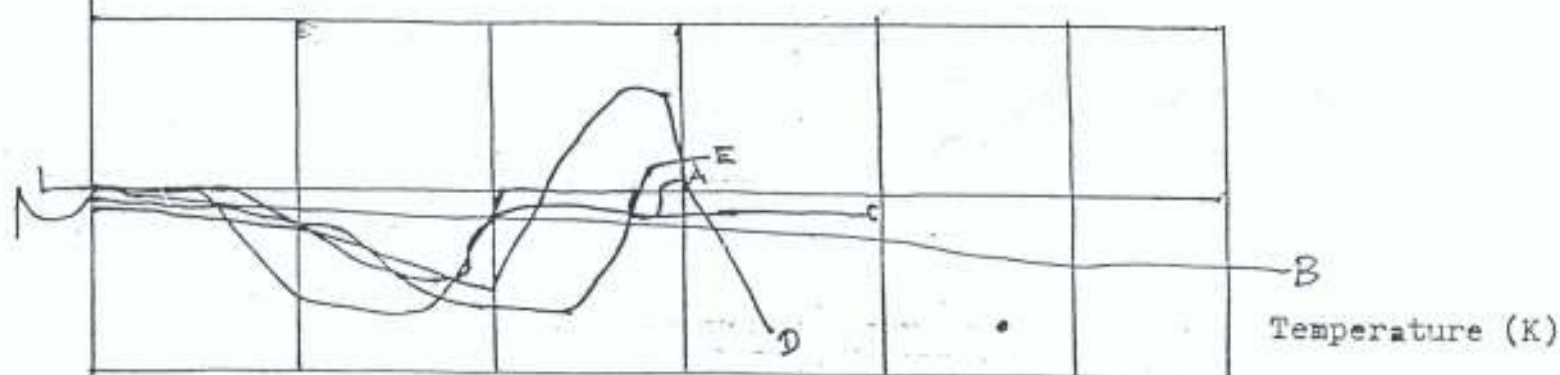


Fig. 6. Dilatation Curves

4.1.5. ASH ANALYSIS

The oxide composition of Lamza, Lafia, Enugu and Australian B coal samples ash are shown in Table 19.

Table 19: Ash Analysis Results

Ash components	Lamza %	Lafia coal %	Enugu %	Australian B coal %
Alumina (Al_2O_3)	21.57	5.94	7.13	39.80
Silica (SiO_2)	58.19	60.06	61.20	52.60
Calcium Oxide (CaO)	Nd	1.68	1.40	0.72
Sodium Oxide (Na_2O)	0.39	0.41	0.14	0.27
Potassium Oxide (K_2O)	Nd	0.96	0.22	0.97
$\text{SiO}_2: \text{Al}_2\text{O}_3$	2.7	10.1	8.6	1.32

nd – not detected

4.1.6. CALORIFIC VALUE

The results of bomb calorimetric tests are shown in Table 12.

4.1.7. SULPHUR ANALYSIS

The results of sulphur analysis are shown in Table 12.

4.1.8. BITUMEN SAMPLE TESTING

With the manual washing method used, the average yield of bitumen obtained from the raw bitumen was found to be 78.54%. Solubility tests with carbon tetrachloride and benzene showed that the average organic matter content of the washed bitumen was 42.22% for carbon tetrachloride and 42.56% for benzene. The inorganic ash content for the washed bitumen was therefore 57.78%, for washing with carbon tetrachloride and 57.74% for

washing with benzene. The results obtained from the solubility tests are shown in Table 20.

Table 20: Solubility tests on Ondo bitumen.

Parameters	10 ml CCl ₄	20 ml CCl ₄	10 ml Benzene	20 ml Benzene
Weight of filter paper (g)	0.8678	0.8527	0.8452	0.8279
Weight of washed bitumen (g)	1.00	1.00	1.000	1.00
Weight of residue and filter paper after filtration (g)	1.4490	1.4272	1.4752	1.3958
Weight of residue (g)	0.5812	0.5745	0.5810	0.5679
Organic matter %	41.88	42.55	41.90	43.21
Organic matter (average) %	42.22%		42.56	

4.1.9 COAL BLENDING

The blending was conducted on the basis of average vitrinite reflectance. The parameters of the coals used in blending design are shown in Table 21, while the theoretical blend formulations obtained are shown in Tables 23 to 30. Table 31 shows the summary of the coal blends obtained and the associated saving in cost on Ajaokuta's proposed annual coking coal import of 1.3 million tons.



Table 21: Coal parameters for blending.

Parameters	Lamza 1 Coal (L1)	Lamza 2 Coal (L2)	Lamza 3 Coal (L3)	Australian) Coal (L4)	West Canada A Coal (L5)	West Canada B coal (L6)	Ogmore Coal (L7)	Bull coal (L8)	Lafia coal (L9)	Ondo) Bitumen (OB)
Avg. vitrinite reflectance (Ro)	*0.70	0.70	0.70	*1.02	**1.62	**1.28	*1.20	*1.28	1.20	-
Ash (db)	7.01	15.51	10.99	5.65	7.2	9.3	3.4	9.5	26.30	57.44
Volatile matter (VM) (daf)	42.41	44.12	43.96	30.52	17.4(db)	21.7(db)	27.4	26.6	32.20	-
Sulphur (db)	0.611	0.83	0.79	0.22	0.39	0.4	0.20	0.38	2.3	1.3
Cost / ton (\$)	***34	34	34	60	***100	***100	**100	***100	*****87.50	*****16.3

Note:

* Estimated: Panaitescu (1991)

** Source: Price et al (1987)

*** Landing cost: Peskett (1999)

**** Source: www.usedbookcentral.com

***** Source: Task Force (1987)

Table 22: Summary of coking properties of coals tested.

Coal/Coal blends	G-Value	ASTM class	ISO NO	Remarks (Price et al, 1987)
Lamza 1 coal	-	High volatile C bituminous coal	811	weakly coking coal
Lamza 2 coal	-	High volatile C bituminous coal	811	weakly coking coal
Lamza 3 coal	-	High volatile C bituminous coal	811	weakly coking coal
Lamza 1 coal + 15% Ondo Bitumen	0.971	-	812	coking coal
Australian coal	-	Medium volatile bituminous coal	522	medium coking coal
Australian coal + 10% OB	1.024	-	523	coking coal
Australian coal + 15% OB	0.992	-	523	coking coal

Table 23: Binary blend of Lamza 1 coal and Ondo bitumen.

Proportion of Coals		Sulphur		Ro		VM		Ash		Cost (\$)		Organic Bitumen used %
L1	OB	L1	OB	L1	OB	L1	OB	L1	OB	L1	OB	
0.85	0.15	0.6	0.195	0.595	0	36.05	0	6.12	48.82	28.9	2.45	6.38
Total		0.89		0.60		36.05		14.74		\$31.35		

Note: The constraints on blending are - Ash, volatile matter and average vitrinite reflectance (Ro).

Table 24: Binary blend of Australian coal and Ondo bitumen(OB).

Proportion of Coals		Sulphur		Ro		VM		Ash		Cost(\$)		Organic bitumen used %
L4	OB	L4	OB	L4	OB	L4	OB	L4	OB	L4	OB	
0.90	0.10	0.20	0.13	0.92	0	27.47	0	5.09	5.744	90	1.63	4.23
Total		0.33		0.92		27.47		10.83		91.63		

Note: Constraint on blending – ash content.

Table 25: Binary blend of Ogmore and Lafia coals

θ	m	n	L7	L9	R	$\geq 0, DR$	A	$\leq 0, DA$	V	$< 0, DV_L$	$> 0, DV_U$	S	$\leq 0, DS$	C	$\leq 0, DC$	DC_A	Constraints violated
0			1.000	0	1.2	0.25	3.40	-8.60	27.40	+0.3	+3.60	0.20	-1.0	100	0	0	V
1			0.9997	0.0003	1.2	0.05	3.40	-8.60	27.40	+0.3	3.60	0.20	-1.0	100	0	0	V
11			0.9636	0.0364	1.2	0.05	4.23	-5.77	38.12	-10.42	7.82	0.28	-0.62	99.55	-0.46	-0.46	V
21	1		0.8716	0.1284	1.2	0.05	6.34	-3.66	28.02	-0.32	2.28	0.47	-0.43	98.40	-1.61	-0.16	no constraint
31	2		0.7347	0.2653	1.2	0.05	9.48	-0.52	28.67	-0.97	1.63	0.76	-0.14	96.68	-3.32	-0.72	no constraint
41			0.5696	0.4304	1.2	0.05	13.26	+3.26	29.47	-1.77	0.83	1.10	0.11	94.67	-5.38	-0.06	A
36	3	1	0.6545	0.3455	1.2	0.05	11.31	1.31	29.06	-1.361	1.24	0.93	0.3	95.68	-4.32	1.06	A, S
33.5		2	0.6954	0.3046	1.2	0.05	10.38	0.38	28.86	-1.16	1.44	0.84	-0.06	96.19	-3.81	0.51	no constraint
32.25	4		0.7153	0.2847	1.2	0.05	9.92	-0.08	28.77	-1.07	-1.53	0.80	-0.1	96.44	-3.56	0.24	no constraint
32.8754		3	0.7054	0.2946	1.2	0.05	10.15	0.15	28.81	-1.11	1.49	0.82	-0.08	96.32	-3.68	-0.12	A
32.5625		4	0.7103	0.2897	1.2	0.05	10.03	0.03	28.79	-1.09	1.51	0.81	-0.09	96.38	-3.62	0.06	A
32.40625	5		0.7128	0.2872	1.2	0.05	9.98	-0.02	28.78	-1.08	1.52	0.80	-0.1	96.41	-3.59	0.03	optimum

Table 26:

Binary blend of Bulli and Lamza 1 coals.

θ	m	n	L8	L1	R	DR	A	DA	V	DV _i	DV _{ij}	S	DS	C	DC	DC _k	Constraints
0			1.0000	0	1.28	0.13	9.5	0.5	26.60	1.1	3.70	0.38	-0.52	100	0	-	v
1			0.9997	0.0003	1.28	0.13	9.5	-0.50	26.60	1.1	3.70	0.38	-0.52	99.98	-0.02	-0.02	v
11			0.9636	0.0364	1.26	0.11	9.41	-0.59	27.18	0.52	3.12	0.40	-0.50	97.60	-2.40	-2.38	v
21	1		0.8716	0.1284	1.21	0.06	9.18	-0.82	28.63	-0.93	1.67	0.44	-0.46	91.53	-8.47	-6.07	no constraint
31			0.7347	0.2653	1.13	-0.02	8.84	-1.16	30.79	-3.09	-0.49	0.49	-0.41	82.49	-17.51	-9.04	v, R
26	2	1	0.8078	0.1922	1.17	0.02	9.02	-0.98	29.63	-1.94	0.64	0.46	-0.44	87.31	-12.69	+4.82	No constraint
23.5		2	0.8410	0.1590	1.19	0.04	9.10	-0.89	29.11	-1.41	1.19	0.45	-0.45	89.51	-10.49	+2.20	no constraint
28.50		3	0.7723	0.2277	1.14	0	8.93	-1.07	30.20	-2.50	-0.1	0.48	-0.42	84.97	-15.03	-2.34	optimum
29.75		4	0.7538	0.2462	1.14	-0.01	8.89	-1.11	30.49	-2.70	0.19	0.49	-0.47	83.75	-16.25	-1.22	R, V
29.125		5	0.7631	0.2369	1.14	-0.01	8.91	-1.09	30.35	-2.65	0.05	0.48	-0.42	84.36	-15.64	0.61	R

Table 27: Binary blend of Ogmore and Lamza 1 coals.

0	m	n	L7	L1	R	DR	A	DA	V	DV _L	DV _U	S	OS	C	DC	DC _A	constraints
0			1.000	0	1.2	0.05	3.40	-8.60	27.40	-0.3	+3.60	0.20	-0.7	100	0	-	V
1			0.9997	0.0003	1.2	0.05	3.40	-8.60	27.40	+0.3	+3.60	0.20	-0.7	100	0	-	V
11	1		0.9636	0.0364	1.18	0.11	3.53	-6.47	27.95	-0.25	2.35	0.22	-0.58	97.60	-2.40	-2.40	no constraint
21			0.8716	0.1284	1.14	-0.01	3.86	-6.14	29.33	-1.63	0.97	0.21	-0.69	91.53	-8.47	-6.07	R
16	2		0.9240	0.0760	1.16	0.01	3.67	-6.33	28.54	-0.84	1.76	0.25	-0.65	94.98	-5.02	-3.45	no constraint
18.5	3		0.9455	0.0545	1.17	0.02	3.60	-6.40	28.22	-0.52	+2.08	0.23	-0.67	96.40	-3.60	+1.42	no constraint
19.75		1	0.8858	0.1142	1.14	-0.01	3.81	-6.19	29.11	-1.41	1.19	-0.63	-0.27	92.46	-3.94	0.34	R
19.125			0.8927	0.1073	1.15	0	3.79	-6.21	29.01	-1.31	1.29	-0.63	-0.27	92.91	-7.09	3.15	optimum

Table 28: Ternary blend of Western Canada A, Lamza 1 and Lafia coals.

θ	β	m	n	L5	L1	L9	R	DR	A	DA	V	DV _L	DV _U	S	DS	C	DC	DC _A	constraints
0	30			1.0000	0	0	1.62	0.26	7.2	-2.8	17.4	10.3	12.9	0.39	-0.51	100	0	0	V
1	30			0.9997	0.0003	0	1.62	0.26	7.2	-2.8	17.4	10.3	12.9	0.39	-0.51	100	0	0	V
11	30			0.9636	0.0273	0.0009	1.58	0.43	7.15	-2.85	17.92	+9.78	12.38	0.40	-0.50	97.37	-2.63	-2.63	V
21	30			0.8716	0.0963	0.0321	1.52	0.37	7.79	-2.21	20.28	+7.42	10.02	0.49	-0.41	93.24	-6.76	-4.12	V
31	30			0.7347	0.1990	0.0663	1.41	0.26	8.43	-1.37	23.36	+4.34	6.94	0.60	-0.30	86.04	-13.96	-7.20	V
41	30			0.5696	0.3228	0.1076	1.28	0.13	9.19	-0.81	27.07	0.63	-3.23	0.73	-0.17	77.35	-22.65	-8.69	V
51	30	1		0.3960	0.4530	0.1510	1.14	-0.01	10.0	0	30.96	-3.26	0.66	0.87	-0.30	68.21	-31.79	-9.14	no constraint
46	30			0.4826	0.3881	0.1293	1.21	-0.06	9.60	-0.40	29.02	-1.32	1.28	0.80	-0.10	72.77	-27.23	+4.56	no constraint
48.5	30			0.4391	0.4207	0.1402	1.17	0.02	9.80	-0.20	30	-2.30	+0.30	0.83	-0.07	70.48	-29.52	-2.29	no constraint
49.75	30		1	0.4175	0.4369	0.1456	1.16	0.01	9.90	-0.10	30.48	-2.78	-0.18	0.85	-0.05	69.34	-30.66	-1.14	V
49.125	30		2	0.4283	0.4288	0.1429	1.38	0.23	9.85	-0.15	30.98	-3.28	0.68	0.85	-0.05	69.91	-31.57	0.57	V
48.962	30		3	0.4311	0.4267	0.1422	1.17	0.01	9.83	-0.17	30.18	-2.48	0.12	0.85	-0.05	70.06	29.44	0.15	V
53.813	30	2	4	0.4403	0.4444	0.1153	1.16	0.01	9.32	0.68	30.22	-2.52	0.08	0.80	-0.10	69.23	-30.77	-0.83	optimum

Table 29: Binary blend of Bulli and Lamza 2 coals.

θ	m	n	L8	L2	R	DR	A	DA	V	DV _L	DV _U	S	DS	C	DC	DC _A	Constraints
0			1.0000	0	1.28	0.13	9.50	-0.5	26.60	1.10	3.70	0.38	-	100	0	-	V
													0.52				
1			0.9997	0.0003	1.28	0.13	9.50	-0.5	26.60	1.10	3.70	0.36	-0.52	99.98	-0.01	-0.02	V
11			0.9636	0.0273	1.25	0.10	9.58	-0.42	26.84	0.86	3.46	0.40	-0.50	97.29	-2.71	-2.69	V
21			0.8716	0.1284	1.21	0.06	10.27	0.27	28.85	-1.15	1.45	0.44	-0.46	91.53	-8.47	-5.76	A
16			0.9240	0.0760	1.24	0.09	9.96	-0.43	27.93	0.23	2.37	0.41	-0.49	94.98	-5.02	-3.50	no con- straint
18.5			0.8993	0.1007	1.22	0.07	10.10	0.10	28.36	-0.66	1.94	0.43	-0.47	93.35	-6.65	-1.63	A
			0.9121	0.0879	1.23	0.08	10.03	-0.03	28.74	-0.44	2.16	0.42	-0.48	94.20	-5.80	+0.85	A
17.25																	
			0.9181	0.0619	1.23	0.08	9.99	-0.01	28.03	-0.33	2.27	0.42	-0.48	94.59	-5.41	0.39	optimum
16.625																	

Table 30: Binary blend of Bulli and Lamza 3 coals.

θ	m	n	L8	L3	R	DR	A	DA	V	DV _L	DV _U	S	DS	C	DC	DC ₃	constraints
0			1.0000	0	1.28	0.13	9.50	-50	26.60	1.1	3.70	0.38	-0.52	100	0		V
1			0.9997	0.0003	1.28	0.13	9.50	-0.50	26.60	1.1	3.70	0.38	-0.52	99.99	-0.01		V
11			0.9636	0.0274	1.25	0.10	9.46	-0.54	26.83	0.86	3.46	0.39	-0.51	97.29	-2.71	-2.7	V
21	1		0.8716	0.1284	1.21	0.06	9.69	-0.31	28.93	-1.13	1.47	0.43	-0.47	91.53	-8.47	-5.76	no constraints
31			0.7347	0.2653	1.13	-0.02	9.35	-0.65	29.01	-1.31	1.29	0.45	-0.45	88.10	-11.90	-3.42	V
41	2	1	0.5696	0.4304	1.03	-0.12	10.1	+0.14	39.07	-6.37	6.37	0.56	-0.34	74.59	-28.41	-16.51	V
36	3	2	0.6545	0.3455	1.08	-0.07	10.0	+0.10	32.60	-4.90	-2.30	0.52	-0.38	77.20	-20.80	-5.61	R, A
33.5		3	0.6954	0.3046	1.10	-0.05	9.95	-0.05	31.89	-4.19	-1.59	0.50	-0.30	80.00	-20	2.70	V
32.25	4	4	0.7153	0.2847	1.11	0.02	9.79	0.02	29.99	-2.29	0.31	0.46	-0.44	87.12	-12.90	-1.21	optimum
29.437		5	0.8010	0.1971	1.16	0.01	9.80	-0.20	30.05	-2.35	-0.25	0.46	-0.44	86.87	-13.13	-0.25	V

Table 31: Blend design formulations and savings in cost realised.

Blend	Lamza 1 %	Lamza %	Lamza %	Lafia/Obi %	Ondo bitumen %	Bulli coal %	Ogmore Coal %	West Canada coal %	Cost savings per ton (\$)	Cost saving for 1.3 million ton (N billion)	Remarks
1.	22.77					77.23			15.03	2.70	no carbonization constraints violated.
2.	44.44			11.53				44.03	30.77	5.53	no carbonization constraints violated.
3.	10.73						89.27		7.08	1.27	no carbonization constraints violated.
4.				28.72			71.28		3.59	0.64	no carbonization constraints violated.
5.			28.47			71.53			12.90	2.31	no carbonization constraints violated.
6.		8.19				91.81			5.41	0.97	no carbonization constraints violated.
7.	85.00				15.00				68.65	12.31	Excessive Ash, low volatile matter are constraints

NOTE: 1\$ = 138 SOURCE: ThisDay(2004)

4.2 DISCUSSION OF RESULTS

For a fruitful discussion of the results obtained on the coals studied, it is necessary to describe the cokeability of the coals on the basis of the International Standard Organization (ISO) chart of coal classification. The ISO classification was done by determining the class, sub-group and group numbers of each coal. The class number was determined by using volatile matter content (dried ash free) for the Australian coal having volatile content less than 33%. For Lamza coal with volatile matter content in excess of 33%, the class number was determined by using the calorific value of coal. The sub-group numbers were determined for the coals and their blends with bitumen on the basis of their dilatation percent, while caking power in terms of free swelling index was used to determine the group numbers. A combination of these three numbers in the order of class number, group number and the sub - group number form the ISO code numbers for the coals and their blends with bitumen. The ISO codes of the various coals considered in this work are shown in Table 32.

In ASTM classification, Lamza coal is a high volatile C bituminous coal while the Australian coal is a medium volatile bituminous coal. The class of Lamza coal was determined by using the calorific value, while that of Australian coal was determined on the basis of its volatile matter content. Lafia coal is also a medium volatile C bituminous coal on the basis of its calorific value. Lamza coal has the advantage of lower ash than Lafia coal.

Table 32: ISO classification.

Coals and Coal Blends	ISO No			Remark
	Class	Group	Sub-group	
Bulli coal	4	3	3	self-coking
Australian coal	5	2	2	medium coking
Australian coal + 10% Bitumen	5	2	3	coking
Australian coal + 15% Bitumen	5	2	3	coking
Lamza 1 coal	8	1	1	weakly coking
Lamza 2 coal	8	1	1	weakly coking
Lamza 3 coal	8	1	1	weakly coking
Lamza 1 coal + 15% Bitumen	8	1	2	medium coking

4.2.1 PROXIMATE ANALYSIS

The inherent moisture content of Lamza coal samples is observed to be similar to that of Indian Jharia coal samples having 1.5 - 2.2%, but the ash content of the former is lower than the 20 - 25% determined for the latter. In terms of volatile content, Lamza samples exceed the 36 - 40% range for Jharia samples (Moitra et al, 1972). In comparison with the low rank Australian Loy Yang Coal with 12.80% moisture and 49.90% volatiles, Lamza coal has lower contents of these components; although its ash contents exceed the 1.10% for Loy Yang samples (Xiaofeng et al, 1998). It is also observed that the ash content of Lamza coal samples is less than 17.52% determined for a prime coking Indian coal. However, the Indian coal is medium volatile with 24.01% volatiles as against the over 42% volatile in Lamza coal (Prasad et al, 1992). The volatile content of Lamza coal is noted to be higher than 38.30% for the Polish gas flame coal whose coking

properties was successfully upgraded with coal tar pitch (Bujnowska et al, 1992). The ash content of 15.9% determined for Lafia coal greatly exceeds that of Lamza coal. However, Okaba and Orukpa coals ash of 8.8% and 6.5% are lower than that of Lamza coal. Enugu coal ash of 11.30% exceeds those of Lamza 1 and 3 samples (Afonja, 1996). Coals with volatile matter (33 - 48%) similar to Lamza coal are commonly used as blend components with low volatile strongly caking coals (Aderonpe, 1996). Ash content is regarded as one of the four most important parameters to evaluate the quality of a coal. The ash content of main coals carbonised to produce coke in Japan (7.2 - 9.6%) are less than that of Lamza coal (Katsuhiko et al, 1987).

The ash content of Lamza coal is lower than that of Lafia coal, thus making it a better choice in blending with prime coking coal to produce metallurgical grade coke. The high volatile content of the Lamza coal is advantageous in blending with low volatile prime coking coal such as the Western Canada A coal (Price et al, 1987). Additionally, coals with high volatile matter values (i.e. 39.4 and 41.8%) close to that of Lamza coal have been used in Japan to produce coke that ensured the most efficient blast furnace operation. However, the ash contents of the coals are lower than that of Lamza (Katsuhiko et al, 1987). It is therefore evident that Lamza coal can serve as a blend component to produce metallurgical grade coke.

4.2.2 FREE SWELLING INDEX

On the basis of FSI, Lamza coal belongs to Group No. 1 of ISO classification (Panaitescu, 1991). The free swelling index of 1.5 determined for Lamza samples exceeds the 0.5 determined for Enugu coal, but is lower than 6 - 9 for Lafia coal (Afonja, 1996). Lamza also shows greater caking power than Onyeama and washed Enugu with free swelling numbers of 1, and Okaba coal with zero swelling number (Aderonpe, 1996). It is also observed that Lamza crucible swelling number is far lower than that of the prime coking UK Ogmores coal that was successfully blended on bench scale with Enugu and Okaba coals (Ndaji et al, 1987). The crucible swelling number was not considered a factor in monitoring the effect of coke additive on coals' cokeability in tests conducted in Poland and Germany (Bujnowska et al, 1992; Weskamp et al, 1987).

The crucible numbers of coals used for cokemaking in India exceeds that of Lamza coal ranging from 3 to 8, while a typical French coal mixture for cokemaking has 6.5 crucible swelling number (CSN) (Podolak, 1987). The CSN of western Canada binary blends exceeds that of Lamza coal ranging from 5.5 - 8.5 (Price et al, 1987). In pilot scale carbonisation tests conducted on Indian coals, CSN was not considered an important laboratory scale coking test prior to cokemaking (Moitra et al, 1972). Addition of 10 and 20% coal tar to Polish gas flame coal had no effects on CSN (Bujnowska et al, 1991). Addition of bitumen to Lamza coal was also observed to produce no effect on the CSN of the samples.

Studies by Echterhoff et al showed that there is no clear relationship between free swelling index and dilatation behaviour for some German coal blends. While a coal blend with an FSI of 4, which far exceeds the FSI of Lamza coal gave a dilatation of -13%, another blend with FSI of 4.5 gave a dilatation of 5%. South American coals with higher swelling indices than Lamza coal have been found to exhibit only contraction during dilatation tests. For example, coals with FSI of 4.5 and 3.5 to 5 produced -29 and -10 to -30 contractions in comparison to Lamza 1 - 18% contraction (Loison et al, 1989).

4.2.3 GIESELER FLUIDITY

Only Lamza 1 coal was found to show Gieseler plastic characteristics on addition of varying amount of bitumen. Addition of 15% and 20% bitumen produced Gieseler fluidity of 223 ddpm and 838 ddpm, respectively. These increases in fluidity are small in comparison to the Gieseler fluidity of 27,000 ddpm determined for the coking Canadian Nova Scotia coal. However, the fluidity increase is observed to be greater than the fluidity of 1.9 - 195 ddpm determined for western Canada coking coals (Price et al, 1987). The fluidity of 27,600 ddpm determined for the washed Lafia coal far exceeds the fluidity of 223 ddpm and 838 ddpm obtained on Lamza 1 coal with bitumen. However, Enugu, Orukpa and Okaba were also found to have zero Gieseler fluidity as received (Afonja, 1996). The good fluidity of 1,000 - 1,500 ddpm obtained for the Australian Ilawarra coal samples showed them to be self-coking coals (BHP Publication, 1998). Addition of 10% and 20% coal tar pitch

to the Polish gas flame coal increased the fluidity by 6 ddpm and 58 ddpm respectively (Bujnowska et al, 1992). The Gieseler fluidity of prime coking coals indicated by Afonja ranged from 60 - 1000 ddpm (Afonja, 1996). For the addition of bitumen to improve cokeability of German coal blends, Gieseler plastic test was not considered in evaluating the effect of bitumen addition (Weskamp et al, 1987).

From the foregoing discussion, it can be deduced that coking coals in use all over the world have varying Gieseler fluidity range which include 223 ddpm determined for Lamza 1 + 15% bitumen. The addition of 15% bitumen therefore produced a blend with sufficient Gieseler fluidity to produce a metallurgical grade coke on carbonisation. Addition of 15% bitumen to the medium coking Australian coal raised its Gieseler fluidity to more than 19000 ddpm. The coal mixture produced therefore had a fluidity close to that of Nova Scotia coal and may produce a metallurgical grade coke on carbonisation (Price et al, 1987). The Gieseler fluidity test on the Chinese Wugong coal gave 13,800 ddpm in comparison with Lamza 1 coal blend with 15% bitumen of 223 ddpm. However, the Chinese Chenggyuan coal that contracted only in dilatometric test gave only 3.7 ddpm fluidity (Zhou, 1987).

4.2.4 RUHR DILATATION

The Lamza coal samples contracted only during Ruhr dilatometry test, while the medium coking Australian coal exhibited some dilatation below the X-axis. Addition of 15% bitumen raised the total dilatation of Lamza 1 coal by 18% and that of Australian coal by 28%, with no effect on Lamza 2 and 3

samples. The G-values calculated were 0.971 and 0.992 for the Lamza 1 and Australian blends respectively. The G-values of 0.954 and 0.973 calculated for the blends of German coals with 5% and 8% bitumen are similar to the G-values calculated for the Lamza 1 and Australian coal blends with bitumen (Weskamp et al, 1987). Enugu, Okaba and Orukpa coals have zero dilatation, while the unwashed Lafia coal has 12% dilatation (Afonja, 1996). Typical American coking coals exhibit better dilatation behaviour than Lamza 1 coal blend with bitumen. For example, in America a high volatile bituminous coal was found to have 220% dilatation and a medium volatile coal had 275% (Lindert et al, 1992).

In fact, the studies by Echterhoff et al on two coal blends having higher dilatations of 13% and 5% (which exceeds the dilatations of Lamza 1 blend with 15% bitumen) showed that increase in coke stability is not directly proportional to dilatations percent. The M10 abrasion resistance of the latter was unexpectedly determined to be 5.8% as against 6.2% for the former. Additionally, the M40 index of the former (76.4%) was not much different than for the latter (73.6%) despite the bigger difference in dilatations. Industrial scale carbonisation of a coal blend that contracted only (-13%) also showed that the coke obtained had better M10 abrasion resistance of 5.6%, while its M40 fragmentation resistance index of 73.0% is only 0.6 units less than for the blend with 5% dilatation. The blend of Lamza 1 coal and 15% bitumen dilatation with 0% and contraction of -18% appear to be better than the blend with only -13% contraction (Echterhoff et al, 1992).

According to the tests conducted by Zhou, the Chinese Aiweieh and Wugong coking coals have very good dilatations of 132.3% and 246.1%, respectively, in comparison with the 0% for Lamza 1 coal blend with 15% bitumen. However, the Chinese Queeh Gou and Chengguan coals only contracted. It is also observed that the Gieseler fluidities of Chinese coals are not always proportional to their dilatations. For example, while the Aiweieh coal with 132.3% dilatation gave only 990 ddpm Gieseler fluidity, the Baiyang River coal with 92.0% dilatation gave 3,240 ddpm Gieseler fluidity. However, in contrast, the Wugong coal with 277.7% dilatation gave 13,800 ddpm (Zhou, 1987). Gieseler fluidity is therefore not a sufficient factor to determine the cokeability or otherwise of coals. For example, the blend of Lamza 1 coal with 20% bitumen had a higher fluidity of 838 ddpm but exhibited no dilatation at all. The recording pen only moved along the X-axis.

4.2.5 ASH ANALYSIS

The composition of Lamza coal ash is similar to that of a typical Western Canadian binary coal blend. For example, the SiO_2 , Al_2O_3 , Na_2O content of 58.19%, 21.57%, 0.39% respectively for Lamza coal is similar to 56.38%, 27.2%, and 0.49% for a Canadian blend. Additionally, the $\text{SiO}_2:\text{Al}_2\text{O}_3$ ratio of 2.7 for Lamza coal ash is close to 2.07 for the Canadian blend (Price et al, 1987). The $\text{SiO}_2:\text{Al}_2\text{O}_3$ ratio of 2.7 for Lamza coal ash is also similar to those of Indian coal blends that produced coke that ensure the formation of slag of moderate viscosity and good acidity. The heat requirement for slagging is also moderate for such coke (Moitra et al, 1972). A very high

$\text{SiO}_2:\text{Al}_2\text{O}_3$ ratio also has adverse effects in the production of basic irons (Cottrel, 1980). Alkalies in coke ash is usually restricted to less than 2kg per ton of hot metal (Loison et al, 1989). Potassium oxide which was not detected in Lamza coal ash has more adverse effects on blast furnace operations than sodium oxide (Forsberg, 1987). On the other hand, the potassium oxide content of 0.96% and 0.22% were determined for Lafia and Enugu coals (Table 19).

4.2.6 CALORIFIC VALUE

On the basis of calorific value, Lamza coal is a high volatile C bituminous coal in ASTM coal classification (McGraw – Hill Encyclopedia, 1987). The calorific values of Lamza samples exceeds 5935kcal/kg, 5866kcal/kg and 6045 kcal/kg determined for Enugu, Okaba and Lafia - Obi coals, respectively (Task Force, 1987). For the Canadian, German and Indian coal blends, calorific values were not determined prior to carbonisation (Price et al, 1987; Moitra et al, Weskamp et al, 1987).

4.2.7 SULPHUR ANALYSIS

The sulphur content of Lamza coal is lower than the sulphur content of 1.75 to 6.83% and 1.47% respectively, determined for unwashed Lafia and Orukpa coals. The sulphur content of Lamza coal is also lower than 1.0% for the prime coking coal indicated by Afonja. However, Okaba and Enugu coals sulphur content are lower than that of Lamza (Afonja, 1996). On carbonisation, only 50 - 60% of Lamza coal sulphur will remain in the resulting coke (Loison et al, 1989). The sulphur content of Lamza coal is similar to those of Indian Kanhan valley, East Bokaro and Ramgarh coal samples (Moitra et al, 1972). The sulphur content of Lamza coal is higher than typical Canadian coal blends, which range from 0.27% to 0.38%. However, a blend with 1.04% sulphur was also carbonised in Canada (Price et al, 1987). The sulphur contents of German Zentralkokerei Saar coal blends (0.71 - 0.95%) are similar to that of Lamza coal (Echterhoff et al, 1992). The sulphur contents of Australian low rank Loy Yang and Yallourn coals of 0.23 and 0.21% are much lower than Lamza coal sulphur content (Xiaofeng et al, 1998).

4.2.8 BITUMEN SAMPLE TEST

The ash content of needle pitch in use as a coking additive in Romania is very low (0.3 - 0.4%), in comparison to Ondo bitumen high ash content of about 58% (Dumitrescu et al, 1987). The average yield of bitumen obtained after washing the raw bitumen was 78.54%. The solubility tests showed that the washed bitumen contains only about 42.39% organic matter on average.

Therefore, the manual washing method used was inefficient. It is therefore necessary to develop a cheap mechanized means of washing the raw bitumen on large scale to meet the need of Ajaokuta Steel Plant coke production. At the present 42.39% average organic matter content and a blending rate of 15% bitumen to upgrade Lamza coal, about 195,000 tons of washed bitumen will be needed per annum to upgrade Lamza coal to produce the coke required for the production of 1.3 million tons of steel. If the average organic matter content of bitumen can be improved to 84.78% by mechanized washing method, only 7.5% of bitumen will be required to blend with Lamza coal to produce coke, translating to about 97,500 tons of bitumen annually.

The potency of bitumen's organic matter to upgrade coals' quality is high. At the present blending rate of 15% washed bitumen, the actual organic matter of 15% washed bitumen is about 6.38%, which is relatively small in comparison with the appreciable increase in plastic properties produced on the Lamza coal. The solubility tests showed that both carbon tetrachloride and benzene dissolved bitumen organic content effectively. When the quantity of solvent used was doubled, only negligible increase in the amount of organic matter dissolved was observed.

4.2.9 BLEND DESIGN

Coal blending to produce blends of coal that will produce metallurgical grade coke on carbonisation is commonly practised in steel industries worldwide. In Chinese coal blending, coals with average vitrinite reflectance (R-max) as low as 0.447 and as high as 1.364 are used. For Chinese coals, coals with low average vitrinite reflectance gave good dilatations. For example, the Fukang coal blend with R-max of 0.754 gave a good dilatation of 89.6%, while the Shitanjing coal blend with 1.364 Rmax gave only 26.7% dilatation (Zhou, 1987). The Rmax obtained for the proposed blends with local coals (Tables 26 to 30) are similar to those of Chinese coals and may therefore produce metallurgical grade coke on carbonisation.

Research work conducted in India also showed that there is no clear relationship between average vitrinite reflectance and the coke stability indices. For example, a blend with Rmax of 1.22 produced a coke with M10 and M40 of 10% and 81.8% respectively, while another blend with 1.04 Rmax produced a coke with M10 of 11.4% and M40 of 82.2%. It is observed that the M40 of the latter is better than the former, while the M10 of the former is better than the M10 of the latter. In general, coals with higher Rmax produced coke with better abrasion resistance index M10 (Singh et al, 1987). Studies conducted on the Australian Bulli self-coking coal showed that it has a good reflectance of 1.28 and produced coke of M10 and M40 of 8% and 82%, respectively.

Blend formulations is also conducted in the USA LTV steel company on the basis of average vitrinite reflectance. The minimum allowable vitrinite reflectance is 1.15 and such blends produced coke with acceptable coke stability (Skerl, 1988). Blending of German coals with bitumen had been successfully done to produce good coke (Weskamp et al, 1992). Laboratory scale blending incorporating appreciable amounts of local coals had been conducted by Afonja and Ndaji et al. In the tests conducted by Afonja, 30 percent of low temperature char prepared from Enugu or Okaba coal may be used with a high fluidity coal to produce good metallurgical coke (Afonja, 1996). Bench scale studies also showed that 13% Enugu and 28% Lafia coals can blend with the prime coking Ogmores coal to produce metallurgical grade coke (Ndaji et al, 1987). The specification of a minimum of 1.15 average vitrinite reflectance for coal blends in blend design studies of Tables 26 to 30 agrees with the Japanese Miyazu's method range of 1.1 to 1.2 vitrinite for coal blends to produce good coke (Loison et al, 1989). Blend design on Lamza coal samples showed that up to 44.44% of Lamza 1 coal can blend with western Canada A coal, while up to 28.47% of Lamza 3 coal can blend with prime coking Bulli coal to produce metallurgical grade coke. However only 8.19% of Lamza 2 coal can blend with the prime coking Ogmores coal. These blends translate to savings of several billions of Naira on importation of 1.3 million tons of coking coal in each case.



4.2.10 INTERNATIONAL STANDARD ORGANIZATION (ISO) AND THE AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM) CLASSIFICATIONS

According to ISO classification, Lamza coal belongs to category VII, class 811- a class of weakly caking coals, while Enugu and Okaba coals belong to category VII, class 900- a class of non- caking coals. Addition of 15% bitumen upgraded Lamza coal to category VIB, class 812 – a class of medium coking coals (Panaitescu, 1991). The ISO code for Lamza 1 coal is 811 – a weakly coking coal of ISO group VII, while the ISO code of Lamza 1 coal +15%, bitumen is 821 – a medium coking coal of ISO category VIB. Addition of bitumen therefore upgraded the Lamza 1 coal by 1 step into the group of coking coals. The Australian coal is of ISO code 522 and ISO category VIA - a medium coking coal. Addition of 10% bitumen to the coal produced a coal of ISO code 523, and ISO category VIA – a group of coking coals. Addition of bitumen therefore upgraded the Australian coal by 1 step into the group of self-coking coals. However, the effect of bitumen addition on coals cannot be monitored in ASTM classification since caking and coking properties are not used in the classification.

4.2.11 THEORY OF PLASTIC BEHAVIOUR

From the results obtained in this work, the theory underlining plastic behaviour of the coals and blends tested are discussed in this section. Bitumen consists basically of carbon and hydrogen, and therefore it is similar in composition to coal. Bitumen is thus compatible with coal and will not

constitute a foreign impurity that will reduce coals plastic properties. When two coals are not compatible on blending it will lead to lack of fusibility (Gonzalez-Cimas et al,1987).

Bitumen had been found to have the capacity to donate hydrogen to coal when added to it (Feng, 1987). Experiments had also shown that increasing the H/O ratio of coals improves their plastic properties (Roga, 1958). Therefore, improvement in the plastic properties of Lamza coal should have resulted from the increase of their H/O ratio due to hydrogen atoms donated by bitumen. Experimental studies had also shown that coals containing more than 70% of inertinite cannot have their plastic properties improved by the addition of coking additives. On pyrolysis, coal forms a pyrogenic bitumen which serves as a binder for other maceral particles. The quantity and amount of bitumen present in a coal had been shown to influence the plastic properties of coals. Addition of natural bitumen will increase the quantity of bitumen available in coal during carbonization and will produce greater binding strength and hence stronger coke strength that good plasticity produces. Hydrogen in coal are driven off from coal during carbonization after it must have imparted its plasticity improvement (Valia, 2002).

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The search for coking coals for the production of liquid iron via the blast furnace has triggered off research in many parts of the world. Nigeria is not an exception. Coking coals is a scarce non-renewable energy resource and for now has no substitute in the production of metallurgical grade coke for ironmaking. This is the basis for this work whose findings are summarized as follows.

- The quality of the low grade Lamza coal had been determined in terms of its proximate analysis, cakeability, cokeability, ash composition and heating value. The coal can thus be described as a weakly caking, weakly coking, sub-bituminous coal with the highest heating value of all known local coals.
- Cokeability improvement studies through the modification of plastic behaviour was successfully conducted by adding Ondo bitumen. Optimum effects on plastic characteristics of Lamza coal was obtained by adding 15% bitumen which upgraded the coal to a medium coking coal of ISO No 812 with a G-value coking capacity of 0.971 which is characteristic of coking coal blends that produce metallurgical grade coke. Furthermore, addition of 10% bitumen was found to improve the plastic property of the medium coking Australian coal, upgrading it to a

coking coal of ISO No 523 with a G- value coking capacity of 1.024 which is characteristic of self-coking coals.

- Analysis of Lamza coal ash also showed that it contains lower amounts of the undesirable alkali oxides in comparison with some other local and foreign coals. Additionally, the SiO_2 : Al_2O_3 ratio of Lamza coal ash determined indicates that a good thermal efficiency will be obtained in the blast furnace when coke produced from Lamza coal blend is used for smelting.
- The theoretical blend design formulation studies on the basis of average vitrinite reflectance showed that over N2 billion will be saved in foreign exchange on Ajaokuta annual import of 1.3 million tons of coking coals when 22.77% of low grade Lamza 1 coal blend with 77.23% of Australian self -coking Bulli coal. Additionally, a blend formulation involving 11.53% of the high ash, high sulphur, and predictably expensive Lafia coal, 44.44% Lamza 1 coal and 44.03% western Canada A coal will result in the saving of about N5.53 billion on Ajaokuta's proposed annual coking coal import. Further calculations also showed that 28.47% of Lamza 1 coal will blend with 71.43% of Bulli coal with an estimated saving of N2.31 billion on Ajaokuta's proposed annual import. Also, 8.19% of Lamza 2 coal will blend with 91.81% of Bulli coal with an estimated saving of about N970 million on Ajaokuta proposed annual coal import.

- Blend formulation studies incorporating Ondo bitumen showed that the excessively high inorganic ash content of the bitumen is a major constraint to its usability. For example, when 15% of Ondo bitumen blends with Lamza coal, the actual amount of the organic matter involved is about 6.38%, while the undesirable excess ash content renders the blend unacceptable for blast furnace cokemaking.
- From the results of the research work, low ash, low sulphur and low volatile prime coking coals with high vitrinite reflectance are recommended for import for ternary coal blending with local coals for cokemaking at Ajaokuta when it takes off. When the results obtained in this research work are successfully upgraded on pilot scale, a solution to the critical problem of producing affordable metallurgical grade coke for the economic and sustainable operation of the Ajaokuta Steel Plant when it starts operation would have been found.

5.2 ENVISAGED RESEARCH WORK AND RECOMMENDATIONS

On the basis of the results obtained in this work, further research is recommended in the following areas:

- Considering the promising results obtained in upgrading the weakly coking Lamza coal and the medium coking Australian coal with bitumen, there is an urgent need to develop a cheap mechanized technique to substantially reduce the ash content of ondo bitumen and

thus enhance its usability to produce metallurgical grade coke at Ajaokuta.

- When the extent of Lamza coal reserve is established and a mechanized washing method to substantially wash Ondo bitumen is developed, pilot scale carbonization studies of Lamza coal with Ondo bitumen as a coking additive should be conducted with the coke oven pilot plant at the National Metallurgical Development Centre, Jos, Nigeria.
- Furthermore, when the proposed in-seam exploration of Lafia coal deposit is done, actual bench scale blend formulations involving Lamza and Lafia coals with imported prime coking coals such as western Canada A self-coking coal should be carried out to confirm the results of the theoretical blend formulations emanating from this work.
- In case further exploration or pilot scale carbonisation studies prove Lamza coal and its blends unsuitable for metallurgical cokemaking, cheap medium coking coals of the Australian type can be considered for importation to produce coke at Ajaokuta. The blends of such coals with bitumen have to undergo pilot scale carbonisation tests prior to industrial scale cokemaking.

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APPENDIX CALCULATION FOR G-VALUES

The G-values of Lamza 1 coal +15% bitumen, Australian coal + 10% bitumen, Australian coal + 15% bitumen and Bulli coals are calculated as follows:

1. Lamza 1 Coal + 15% Bitumen

E = Softening temperature

$$= 209 + 273 = 482\text{K}$$

V = Temperature of maximum dilatation

$$= 241 + 273 = 514\text{K}$$

c = % maximum contraction = 18%

d = % maximum dilatation = 0%

But

$$G = \frac{E + V}{2} \times \frac{c + d}{V \times c + E \times d}$$

$$= \frac{482 + 514}{2} \times \frac{18 + 0}{514 \times 18 + 482 \times 0}$$

$$= 498 \times 0.00195$$

$$= \underline{0.971}$$

2. Australian coal + 10% bitumen

E = softening temperature

$$= 214 + 273 = 487\text{K}$$

V = Temperature of maximum dilatation

$$= 257 + 273 = 530\text{K}$$

c = % maximum contraction

$$= 8\%$$

d = % maximum dilatation

= 28

$$G = \frac{487 + 530}{2} \times \frac{8 + 28}{530 \times 8 + 487 \times 28}$$

$$= 508.5 \times 0.002014$$

$$= \underline{1.024}$$

3. Australian coal + 15% bitumen

E = softening temperature

$$= 201 + 273 = 474\text{k}$$

V = temperature of maximum dilatation

$$= 267 + 273 = 540\text{k}$$

c = % maximum contraction

$$= 13\%$$

d = % maximum dilatation

$$= 10\%$$

$$G = \frac{E + V}{2} \times \frac{c + d}{c \times V + E \times d}$$

$$= \frac{474 + 540}{2} \times \frac{13 + 10}{13 \times 540 + 10 \times 474}$$

$$= 507 \times \frac{23}{11760}$$

$$= 507 \times 0.00196$$

$$= \underline{0.992}$$

4. Bulli coking coal

E = softening temperature = $400 + 273 = 673\text{K}$

V = temperature of maximum dilatation = $480 + 273 = 753\text{K}$

c = % maximum contraction = 25%

d. = % maximum dilatation = 20%

$$\begin{aligned} G &= \frac{673 + 753}{2} \times \frac{25 + 20}{753 \times 25 + 673 \times 20} \\ &= 713 \times 0.001398 \\ &= \underline{0.994} \end{aligned}$$