CHARACTERISING COALS FOR COKE PRODUCTION AND ASSESSING COKE

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PREDICTING COKE QUALITY BASED ON COAL PETROGRAPHY, RHEOLOGY AND COKE PETROGRAPHY

Pierre Jordan

A project report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Masters of Science in Engineering.

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DECLARATION

I declare that this research report is my own, unaided work. It is being submitted for the Degree of Masters of Science in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any University.

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Pierre Jordan

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ABSTRACT

Given the high costs and general shortage of coking coals on the domestic and international markets, and because the nature and qualities of many of the coking coals available on the markets are themselves mixed products, conventional mechanisms and tried and trusted formulae for manufacturing coke products based on single coals of known qualities can no longer apply. There is therefore an urgent need to develop more effective techniques for evaluating and assessing the properties of individual coals rapidly and reliably and in a manner that could provide useful data for use in modelling the effect of new coal components in a coke blend. Towards this end, the current research has sought to find more accurate coal characterisation techniques at laboratory scale than currently exists in industry at present.

Seventeen coking or blend coking coals from widely different sources were selected and cokes were produced from them in as close to full scale conventional conditions as possible. Both coals and cokes were analysed using conventional chemical, physical, petrographic and rheological coking methods.

The results indicated that, whilst all coals had acceptable chemical, physical and petrographic properties as evaluated on individual parameters thereby indicating their potential values as prime coking coals, in fact the resultant cokes of some of the coals had properties that disproved this assessment. These anomalies were investigated by integrating all characteristics and statistically evaluating them.

The result [outcome] indicated that the series of coals under review fall naturally into three distinct categories according to rank, as determined by the reflectance of vitrinite, and that the coking coals in each rank category were further characterised by parameters specific to that level of rank. In this way more accurate predictions of coke quality were obtained than has been the case to date when using single set evaluations or previously devised formulae.

On this basis it was concluded that, when selecting coals for coke making, it is essential to first establish the rank of the coal by vitrinite reflectance and then to apply coke evaluating parameters specific to that level of rank. The formulae developed for this purpose held good for all coals tested, however, it remains to be seen whether this applies universally to an even wider source of coals.

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GLOSSARY

BF	Blast Furnace
SAF	Submerged Arc Furnace
%RoVmax	Percentage mean maximum reflectance of vitrinite
%RoR	Calculated Index to incorporate the reactive semifusinite in the reflectance of vitrinite
CBI	Composition Balance Index
M40	Micum drum Index 40
M10	Micum drum Index 10
CRI	Coke Reactivity Index
CSR	Coke Strength after Reaction
R2	Coefficient of Determination
SI	Strength Index
G-Factor	Factor derived from results obtained in the Dilatation test
F-Factor	Factor derived from results obtained in the Gieseler Fluidity test

INTRODUCTION

From the time coal is mined, to the time it is charged as coke to the blast furnace or the submerged arc furnace, many tests can be performed to optimize coke quality. As economics drive blast furnace (BF) and submerged arc furnace (SAF) operators to reduce coke rates, coke quality requirements become increasingly stringent. This requires careful selection of coals and formulation of blends, together with regular monitoring of the quality of coals destined for the coke plant.

In the years gone by much research has been undertaken on understanding the coking process but two fundamental problems remain; (a) how to best characterize coals to predict the quality of coke produced by a given process, and (b) how the individual coal qualities contribute to the overall coal blend which forms the desired coke.

The increase in trade in coking coals in the world today has resulted in the exhaustion of reserves in established coking coal mines and the opening of new and less well-known coking coal mines, the latter with products yet to be evaluated. Furthermore, the impact on mines of constant environmental pressures and social and political changes has resulted in the establishment of many smaller mines with different approaches to mining and environmental control. This scenario has lead to the need for such mines to cooperate in beneficiation and marketing which has resulted in the sale of mixed products to the coke making industry. This "mixed-bag" approach has a significant impact upon the blending of coals for efficient coke-making because the conventional blending mechanisms and tried and trusted formulae, all previously based upon single coals, can no longer be applied.

As a consequence of the above factors, the coke producer is therefore faced with

(a) highly variable qualities of coking coals in the market place and

(b) the necessity to chop and change the source of blend coking coal more frequently and at shorter intervals than in the past.

(c) the cost implications of coking coals and the drive on the part of the steel and ferroalloy producers to decrease raw material input cost.

Under present conditions in industry, the coke producer has little or no time to evaluate each new coal that is acquired for coke making from the market place. The normal time for a coal to be tested and approved for production purposes is about one year.

There is therefore an urgent need to be able to understand the fundamental properties of individual coals rapidly and reliably and in a manner that could provide data for use in modelling the effect of new coal components in a coke blend. In order to achieve this, more accurate coal characterization techniques at laboratory scale have to be found than exist in industry at present (*Mitchell W, Iron 1999).*

Such new systems could also serve as screening mechanisms whereby coals could be evaluated and then either tested further in pilot scale and/or full plant test programs or discarded at the outset. This enhanced selection process would then permit the incorporation of selected coals into a blend without jeopardising the overall coke quality supplied to any given customer.

Attempts to achieve such methods in South Africa have been developed in past decades, for example by Steyn and Smith (Steyn and Smith, 1981) and (Falcon et al, 2004) but no definitive system has emerged that can easily be adjusted to the coal markets as they apply at present. Most of these characterization methodologies concentrate on either the coal or the coke and using only selected parameters. Some of them endeavour to characterise single coals and relate them to their respective cokes but no one has yet to characterise a single coal with respect to its role in a coke blend. One of the major difficulties in the world is to provide the coke producer with a way by which he can evaluate a single coal based on laboratory results and also be able to predict the impact it would have on the blend. A coking blend may include any number of coal parcels (ranging from 2 to 27). To eventually be able to predict the blend behaviour we must first start with the individual coal and be able to predict its behaviour in the process of becoming a coke.

However it must be stated that any one single characterisation method or methodology would probably never be able to fully and accurately predict the coal's behaviour in a selected technological process. It is necessary to understand the fundamentals of coal, its makeup, geological occurrence, initial deposition, climate and plant growth subsequent history and most of all its chemical, rheological and physical properties and how these relate to the technological behaviour of the coal. With this in mind it is clear that the characterisation methodology followed by a coke producer and that followed by a char or calcined anthracite producer would differ in approach as each of these processes differ in their product requirements.

The purpose of this research is to propose a new methodology whereby a single coal can be evaluated to predict its resulting coke qualities with the view to later predict its probable use as a component in a coking blend. With coke qualities needed for different technological uses can vary substantially, this report will focus on the most common coke qualities used by the steel producers as well as those that might have an impact on the ferroalloy producers.

The approach taken in this research is the following:

a. To characterize 17 different coking coals and their coke products through experimentation and advanced testing of both coal and coke as single components.
b. To use modern analytical techniques including coal and coke petrography and to establish the role of carbon bonding and chemico-physical structural analyses of the carbon molecules in relation to an extensive suite of conventional tests and analyses to achieve the above.

c. To provide data that could be of use in modelling the effect of new coal components in a coke blend

To achieve the above the following steps have been taken:

a. Selection of key northern and southern hemisphere coals of known different qualities, grades, types, ranks (ranks within the coking range) and structure (isotropic vs. anisotropic).
b. Heat treatment of individual coals in conditions consistent with coking pilot plant testing procedures in order to produce each coal's specific coke.
c. Analyses of the coals using chemical, physical, rheological, technical and petrographic techniques.
d. Analyse the coke product of all the individual coals using chemical, physical and petrographic techniques.
e. Testing of the coke products for reactivity, behaviour and stability expressed as the following:
    - Coke reactivity index (gas reactivity)
    - Coke strength after reaction (coke behaviour)
    - Micum index (coke stability)
f. Comparability of all results with regards to their influence on coke quality as dictated by both the BF and SAF technologies.
g. Formulation of a coal characterisation methodology which will broaden the understanding of individual coals, the differences in different geographical deposits as well as the rank and the ratio of isotropic to anisotropic carbon structures.

The coals selected for testing include seventeen coals, of which two are South African coals, two Australian coals and thirteen American coals. These coals have been subjected to the following analyses:

1. Proximate analyses.
2. Ultimate analyses.
3. Rheological properties
    a. Free Swell Index
    b. Roga Index
    c. Dilatation (Dilatometer)
    d. Fluidity (Plastometer)
4. Petrographic properties
    a. Maceral composition
    b. Vitrinite reflectance
        i. Classes
        ii. RoV_{max}
        iii. RoR
        iv. Total inerts
        v. Optimum inerts
        vi. Composition balance

5. Physical Properties
    a. Hardgrove Index
6. Ash Fusion Temperature

Each coal was individually carbonized in a 400kg pilot coke oven under the same loading and temperature conditions. The resulting coke product was subjected to the following analyses:

1. Cold strength
    a. M 40 and M 10 (Micum drum index)
    b. I 40 and I 10 (Irsid drum index)
2. Hot strength
    a. CRI (coke reactivity index)
    b. CSR (coke strength after reaction)
3. Chemical analyses
4. Proximate analyses
5. ASTM Stability Factor
6. ASTM Hardness Factor
7. Coke Petrographic Properties
    a. Reflectance
    b. Textural component analyses
    c. Carbon forms.

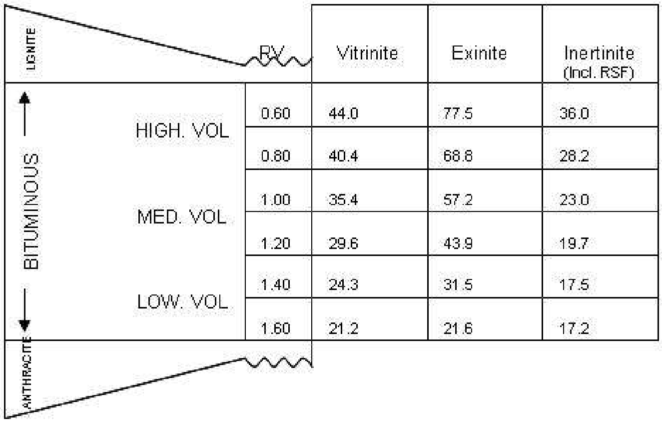
The analytical results have produced quantifiable properties and characteristics, which have been presented in graphic, tabular and statistical forms in chapter 4 and appendix 1. The relationship between the original coals and their resulting coke qualities is discussed in chapter 5.

LITERATURE STUDY

1.1 In South Africa

In general terms the major difference between the Carboniferous coals of the northern hemisphere and the Permian coals of the southern hemisphere lies in the fact that the latter is higher in ash, and inert organic matter content both of which exert a tremendous effect on the coking ability of a coal. There are many more differences, including lower sulphide, pyrite, and chlorine content, but with regard to coke making, a major difference lies in the lower percentage of vitrinite and the percentage of semireactive inertinites. These represent the reactive components of the coal which in principal contribute to the coke quality.

Falcon (1986) showed that, in general, the Gondwana coals do not fit into the previous international classification systems. Most of the Southern African coals are higher in ash (over 10% ash even when washed) and exhibit extremely variable maceral composition and rank. For this reason Falcon and others proposed a new approach namely that all parameters characterising coal relate to three basic or fundamental concepts - grade, type and rank. These three concepts represent the unifying links between coals of all types and origins and, as such they should be used to formulate the basic frame work of any universally accepted system of classification. These new approaches opened new doors to the overall characterisation of coal for the benefit of all coal based technological processes. A good example of this is shown in Figure 2.1. In this diagram the volatile matter content (daf) characteristic of the three maceral groups at various levels of rank within the bituminous range of coal are shown. This figure illustrates that the use of volatile matter alone to indicate the rank of a coal is insufficient in maceral variable coals such as those found in South Africa. For example, a 30% volatile coal may be either a "low volatile" exinite rich coal, a "medium volatile" vitrinite rich coal or a "high volatile" inertinite rich coal.



	RV	Vitrinite	Exinite	Inertinite (Incl. RSF)
HIGH. VOL	0.60	44.0	77.5	36.0
	0.80	40.4	68.8	28.2
MED. VOL	1.00	35.4	57.2	23.0
	1.20	29.6	43.9	19.7
LOW. VOL	1.40	24.3	31.5	17.5
	1.60	21.2	21.6	17.2

Figure 0.1: Volatile matter (daf) on each maceral group, relative to increasing rank

Coal petrographic data which consist essentially of the maceral composition and reflectance value (RoV) are not only the most informative parameters of coal, but they can be used for correlation with certain physical and chemical parameters which are generally determined on coal. Steyn and Smith (1977) showed that certain macerals in coal can be grouped together to form the total reactives. The term "reactives" refers to the behaviour of such materials during the carbonisation process as these macerals change in form become plastic, emitting volatiles and swell. Consequently, the inert material is incorporated and bonded by the swelling reactives to form a porous residue called coke. They also made a discovery that not only the vitrinite and exinite maceral groups are the reactives in coal during carbonation as was believed in the Northern hemisphere, but that a maceral group previously regarded as inert is in fact reactive and the authors termed it "reactive semifusinite"(RSF). Although there was a Russian and American method which simply regarded one third of the total semifusinite as reactive, this proved not to be of assistance in solving correlation problems encountered with inertinite rich South African coals. Steyn and Smith proved that the typical Gondwana coals produce a much better quality coke than that normally expected from low-vitrinite containing coals. However the determination of the amount of reactive semifusinite has always proved to be difficult and the distinction between reactive and inert semifusinite is subjective to a certain degree.

This brings about the fact that errors occur when one petrographer's results are compared to another when using the Steyn and Smith model. Results can inmost cases only be compared when the same petrographer is used for all the results. However it is not always possible to use or have access to the same petrographer. This problem can hopefully be overcome by the use of advanced technologies e.g. by incorporating Raman spectra which can point out the ratio of isotropic and anisotropic bonds in the coal.

Steyn and Smith did, however, develop some independent methods of correlation to obtain the correct amount of reactive semifusinite. Their first method implies the summation of the vitrinite, exinite and the reactive semifusinite to give a percentage total reactives. Their second method implies employing values derived from the graph shown in Figure 2.2 in which the percentage vitrinite is plotted against the percentage of the total semifusinite that is regarded as reactive. To obtain a value for reactive semifusinite, the percentages of reactive semifusinite and inert semifusinite as determined by a maceral analysis, are added together. The percentage vitrinite, as determined during the same maceral analysis, is plotted on the curve. The percentage of semifusinite that corresponds with this point on the curve is that portion of the total semifusinite which is regarded as reactive. This value is then multiplied by the value_for the total semifusinite from the maceral analysis to obtain the reactive semifusinite content in the coal. This new value for the reactive semifusinite, which can differ considerably from the one third as suggested by the Russians and Americans, is then added to the values for vitrinite and exinite to obtain the amount of total reactives. It is, however, of interest to note that for high-vitrinite coals such as the prime coking coals of South Africa, the reactive semifusinite content is close to one third of the total semifusinite, whereas, in some low-vitrinite coking coals of South Africa, the reactive semifusinite content can almost be as high as two thirds.

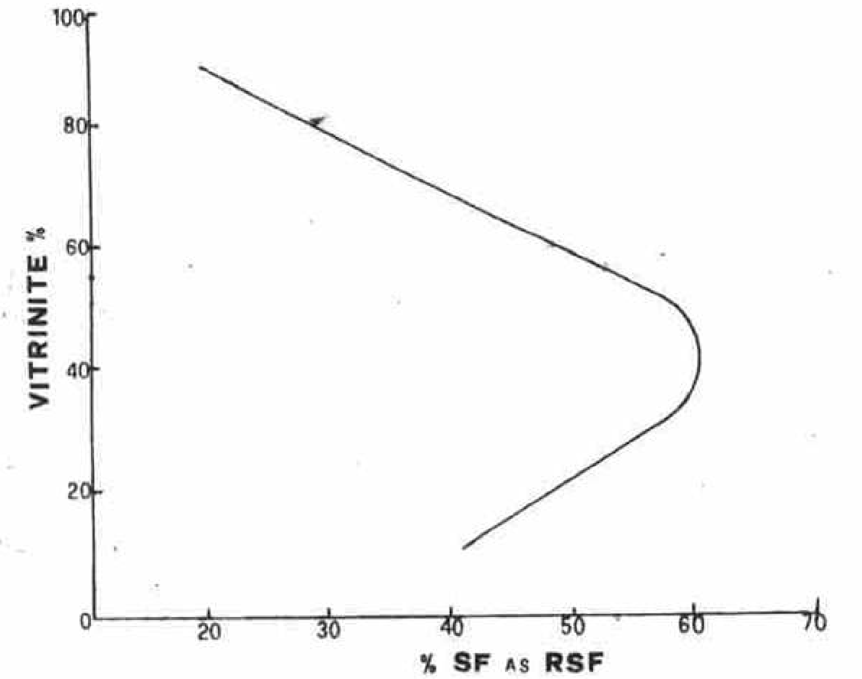


Figure 0.2: Reactive portion of total Semi Fusinite (reactive semifusinite + inert semifusinite) against vitrinite content (Steyn & Smith, 1977)

Method three of Steyn and Smith also concerns values derived from a curve that is shown in Figure 2.3. This gives the correlation between volatile matter (dry basis) and the ratio of reactives/RoV$_{max}$. To obtain the amount of reactives, the percentage volatile matter is plotted on the curve and the corresponding value for reactives/RoV$_{max}$ is derived. The RoV$_{max}$ value multiplied by the value derived from the curve, results in the amount of total reactives. A similar curve can be used where the volatile matter is on a dry, ash-free basis and the reactives on a mineral, matter-free basis. The three values for the amount of reactives as obtained by the three different methods can be averaged, provided that differences between the values are less than three per cent.

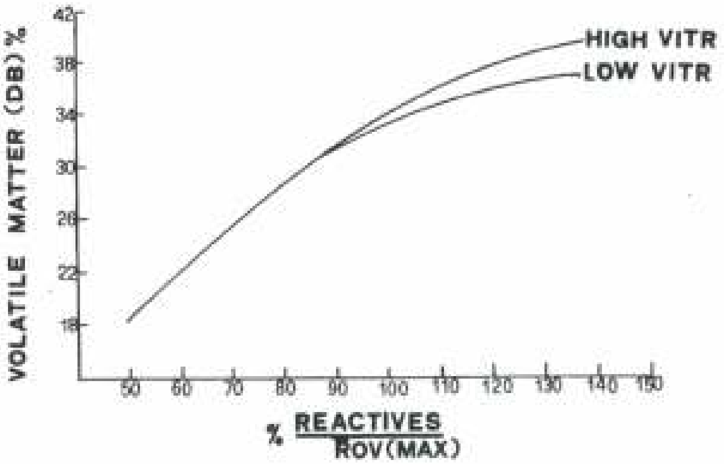


Figure 0.3: Volatile matter content versus. reactives/RoV$_{max}$ (Steyn & Smith, 1977)

The most astonishing correlation Steyn and Smith achieved was to be able to predict some coke properties from the petrographic data. For example they predicted M10 (Micum Index 10) and M40 (Micum index 40). However this model, as is the case with most models for coke predictions, runs on a database from which correlations can be drawn. To date this is probably the most reliable method, but this method has one flaw that this can only predict a coal accurately if that specific type of coal has been entered in the database. The Steyn and Smith model still works well with respect to Gondwana coals because these coals have been included into their database. When new coals and Northern hemisphere coals are entered into their model errors occur. The main reason for this is that the database has not been kept up to date over the last 10 years. The focus from the coke producers perspective is not so much to characterise individual coals but to characterise an individual coal with respect to the contribution or negative effect it might have on the overall coking coal blend.

In order to describe the Steyn and Smith method a brief description must be given on the parameters used to be able to predict coke quality from petrographic data.

The petrographic data required for correlation are firstly the maceral composition expressed in terms of vitrinite, exinite, reactive semifusinite and inerts, and secondly the reflectance types of vitrinite which is a quality parameter for reactives.

The inerts include mineral matter which is calculated from the ash and sulphur content using the simplified Parr’s formula (mm = 1, 05 ash + 0, 55 S). The results obtained by micrometric analysis are expressed in volume percentage. Accordingly to correct for relative density, the calculated mineral matter is divided by two.

The indices calculated from the petrographic data for correlation purposes were the RoR-Index and the Composition Balance Index.

The RoR-Index is the mean maximum reflectance of the reactives at 546 nm. The mean maximum reflectance of the reactive semifusinite is on average 0,3 per cent higher than the associated vitrinite. The exinite group of macerals which have considerable lower influence are only present in small quantities in South African coal.

The mean maximum reflectance of the reactives was accordingly calculated from the vitrinite reflectance and maceral analysis as follows:

$$RoR = \frac{RoV\ (V+E) + (RoV + 0.3)\ RSF}{V + E + RSF}$$

where:

RoR = mean maximum reflectance of reactives.
RoV = mean maximum reflectance of vitrinite.
V = Vitrinite %
E = Exinite %
RSF = Reactive semifusinite %

The second index calculated from the petrographic data was the Composition Balance Index which is a ratio of total inerts in coal to the inerts required for optimum coke strength. The Steyn and Smith calculation differs from those derived in the Northern hemisphere where more the one third of the semifusinite is regarded as reactive and less than two thirds is regarded as inerts.

The first step in calculating the Composition Balance Index is to calculate the percentage distribution of the V-types from the reflectance values obtained on vitrinite, type V5 being all vitrinite with a reflectance from 0,50 to 0,59 etc.

The reactives obtained from the maceral analysis are then apportioned into V-types. Vitrinite and the exinite groups are allotted to V-types in proportion to V-type distribution. Reactive semifusinite is also allotted in proportion to V-type distribution but is on ground of its higher reflectance added to the other reactives by placing it proportionally at 3 V-types higher. All vitrinite and exinite group macerals are allocated to V-types >18 and reactive semifusinite allocated to V-types >15. Those vitrinite and exinite group macerals <18 and reactive semifusinite <15 are regarded as inerts and are added to the inerts derived from the micrometric analysis.

For maximum coke strength the optimum inerts that can be bonded by reactives of each V-type is the ratio obtained if the reactives of the V-type is divided by the optimum ratio of reactives to inerts as listed. The optimum inerts for the coal is the sum total of optimum inerts for all V-types in the coal:

$$\text{Optimum inerts (OI)} = \sum_{i=4}^{18} \frac{R_i}{Q_i}$$

The Composition Balance Index which is the inerts/optimum inerts ratio is therefore derived as follows:

$$\text{Composition Balance Index} = \frac{I}{\sum_{i=4}^{18} \frac{R_i}{Q_i}} \quad \text{where}$$

I = % Total inerts (including vitrinite plus exinite apportioned to V-types >18 and reactive semifusinite apportioned to V-type >15)

R_i = % Reactives of the *i*-th V-type

Q_i = Optimum ratio of reactives to inerts for *i*-th V-type (obtained experimental data)

The family of curves in Figure 2.4 shows the relationship between the petrographic indices of the coal and the Micum indices of coke. In this figure equal coke strength and coke abrasiveness as expressed respectively in terms of the M40 and M10 index are plotted as a function of the RoR and the Composition Balance Index. The solid curves are based on actual coke tests whereas the dotted portion is extrapolation. The reason for referring to M40Y and not to M40 is that the Micum index tests conducted by Steyn and Smith were carried out on +20mm coke particles and not the standard +60mm particles. For a particular coking rate the M40Y is on average 10 per cent lower than the M40.

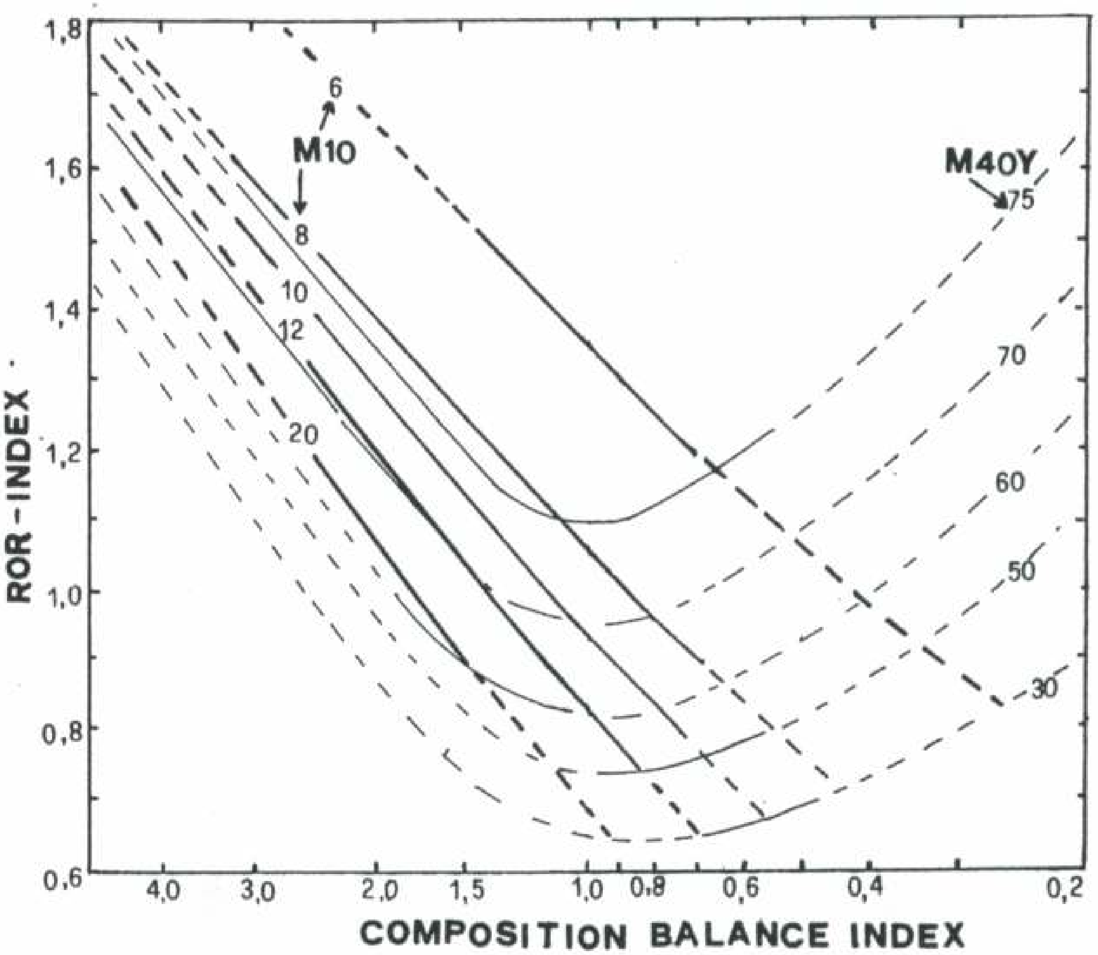


Figure 0.4: Correlation between petrographic indices of coal and Micum indices of coke

Steyn and Smith also attempted to use the same principal to predict a blend. The blend equations are as follows:

Composition Balance Index (CBI) $= \dfrac{\sum_{i=1}^{n} I_i.C_i}{\sum_{i=1}^{n} OI_i.C_i}$ and

Reflectance Index (RoR) $= \dfrac{\sum_{i=1}^{n} R_i.RoR_i.C_i}{\sum_{i=1} R_i.C_i}$ where

I_i, R_i, OI_i and RoR_i are respectively the % inerts, % reactives, optimum inerts and reflectance index for the *i*-th component in the blend and C_i is the fraction of the component.

The above described method was successfully used in the planning of coal blends and for explaining anomalous physical and chemical properties of coal. It was successfully used in the evaluation and characterisation of a wide range of individual coals from the Southern hemisphere.

However the shortcoming of this method is mainly on the blend prediction as most of the individual coal characteristics and properties are not necessarily additive. This method cannot for example be used to predict blend Dilatation and Fluidity which are some of the most important characteristics in a coking coal blend. The aim of this project paper is therefore to try to add to this knowledge and to utilize new methods to characterise individual coals in a way that would lead to the more successful prediction of coking coal blend characteristics.

1.2 International

In the last two decades there has been a revival in certain parts of the research and development on coking coal and especially on the understanding of the influence of coal properties on coke quality mainly guided by the increased quality demands by the blast furnace. Not only are the blast furnace operators making higher demands on coke quality, arc furnace operations in the ferroalloy industry are also doing so. The main reason for the blast furnace demand for higher quality coke is due to the increasing usage of PCI (pulverized coal injection). This results in the fact that coke producers need to produce more un-reactive coke with higher strength after reaction.

Coke plays three major roles in the blast furnace:

1) As a fuel, it provides heat for the endothermic requirements of the chemical reactions and the melting of slag and metal.
2) As a chemical reducing agent, it produces gases for the reduction of the iron oxides, and
3) As a permeable support, it acts as the only solid material in the furnace that supports the iron bearing burden and provides a permeable matrix necessary for the slag and metal to pass down into the hearth and for hot gases to pass upward into the stack.

The first two can be substituted in theory by any material that can perform the same i.e. supply heat as a fuel and secondly produce gases that can reduce the iron oxide. Some examples are the use of oil, gas, plastic and coal. But as a permeable support however there is no other substitute available.

With the increase in the use of PCI the coke rate has dropped and this has an effect on the coke quality. The coke now needs to be almost inert, meaning it does not need to be the best fuel and does not need to supply all the gases for reduction. It does however need to be much stronger. With reduction in coke rate there is less coke that needs to carry the full burden of the ore and slag on top. This in return provides a greater challenge in that the coke producers are now required to produce high strength and more stable coke. This is quantified by the M40 and M10 (MICUM) indices and the CRI (Coke Reactivity Index) and CSR (Coke Strength after Reaction) Index. Examples for the typical coke size and strength values for European blast furnaces are given in Table 2.1 below.

	European Ranges
Mean Size (mm)	47 - 70
M40 (+60mm)	>78 - >88
M10 (+60mm)	<5 - <8
I40	53 - 55
I20	>77.5
DI 150/15	83 - 85
ASTM Stability	60 - 64
CSR	>60
CRI	20 - 30

Data taken from: O'Donnell and Poveromo, 2000 (data presented from AISI coke quality survey)

Table 2.1 Required physical properties of blast furnace coke in current operations

Although coke mechanical strength indices provide blast furnace operators with a useful assessment of coke performance, they form only part of the complex overall picture. The main reason for this is that the tests designed or used to assess coke's mechanical strength do not simulate the condition in the blast furnace i.e. temperature, gas flow and concentration and load of raw material to name a few. Hence the values obtained from these tests are a guideline only and in the most cases hold true to that specific operation, as a measurement and cannot be directly compared to the same values and performances of other operations.

The importance of the high temperature properties of coke was established by the Japanese Steel Industry from the dissection survey of three blast furnaces that were quenched while in operation. As a result of this a combined test for measuring coke reactivity and post-reaction strength was introduced by the Nippon Steel Corporation in the 1970's. This method will be elaborated on in the chapter discussing test methods under CRI and CSR. Various authors have found a high degree of correlation between these two indices. Menéndez et al., (1999) showed that, from a series of more than 60 cokes produced from single coals of different ranks and geographical origin, and from complex coal blends, that a r^2 = 0,977 in correlation, was achieved between the CRI and CSR indices, the r^2 value a number from 0 to 1 that reveals how closely the estimated values for the trendline correspond to the actual data. A trendline is most reliable when its r^2 value is at or near 1 this is also known as the "coefficient of determination".

Several authors have also demonstrated the relevance of CSR in the blast furnace operation to maintain permeability when running under constant or higher production rates. For instance it was found that when the CSR index decreases the gas permeability resistance or impermeability index increase (Diez, 2001).

The larger blast furnaces operating with low coke rates (high PCI) and high production rates also showed the importance of CSR indices. Most blast furnace operators will agree that with an increase in the CSR index of a coke feed to the blast furnace the injected coal levels can be increased and the low coke rate maintained. However CSR indices below 60% in most cases are not acceptable because of the resultant high pressure losses and reduced furnace permeability.

Although coking conditions, for example bulk density, coking time, preheating of the charge, and the incorporation of non-coal materials, do minimize the differences in coal properties to obtain good coke properties, the selection of the right optimum coal for the selected coal blend is a major priority and a science practised by coke producers.

Summary of coke prediction models

Currently practice in coke making demands a coal blend that is low in cost, produces a high quality coke, and provides a safe oven operation. Coal blending has been adopted by the industry partially because of the limited availability and high cost of prime coking coals and also because of the continued demand for better quality coke for the blast furnace which cannot be obtained by a single coal. Coal blending varies in the number of coals used (three to twenty seven) and in their proportion, rank, coking properties, and geographical origin.

Coal selection and the composition in the blend are major factors controlling coke properties (physical and chemical). As aids to coal selection and coke quality prediction, several mathematical models are available or could be produced. They are divided into two groups according to the coke properties involved. The first group of models focuses on the prediction of cold mechanical coke strength (i.e., MICUM indices). The second group of models uses the CRI and CSR indices as coke quality parameters. As far as can be gathered, no prediction model has reached universal application. Some coals and most blends show significant deviations between values predicted by a model and values obtained experimentally. However, almost all coking plants have, for internal use, some form of a model based on coal rank, rheological properties, petrology, and ash chemistry. However it needs to be said that these models are based only on the coals used in a particular coke operation.

Strength is the most important physical property of coke. For this reason many researchers have attempted with considerable effort, to correlate with strength coal rank and type in terms of total inert content, rheology as indicated by maximum fluidity, total dilatation, and parameters deduced from petrographic compositions of coal. Based on the complexity of the relationship between all these parameters, some mathematical models use petrographic compositions in the evaluation of the coal coking potential and the prediction of coke strength.

Petrographic analyses for the prediction of coking properties have classified macerals in to reactives and inerts. The work of Stopes (1935) provided the first basis for a definition of coal composition based on the ‘‘maceral concept’’. This represented a major advance into the understanding of how an optimum ratio of reactive and inert components affects coal carbonisation properties and behaviour. The term ‘‘reactives’’ includes those macerals which soften or melt on heating and bind ‘‘inerts’’ (those macerals that remain unchanged on heating) and then re-solidify into a sponge like, solid carbon product. Consequently, coke structure should be considered as a composite material where most of the coke constituents came from the reactive materials (binder) and a much lower proportion from the material which acts as a filler (inerts) during the carbonisation process. To obtain a good coke, a known proportion of reactive and inert material is required and the optimum amount of each one will vary with the type of reactive macerals much like concrete which consists of stone, sand and cement. In general, reactive macerals includes vitrinite, liptinite, and one-third of semifusinite which as previously mentioned is called semi-reactive-fusinite, while the inert coal constituents during carbonisation are two-thirds of semifusinite, fusinite, macrinite, micrinite, inertodetrinite, sclerotinite, and mineral matter. (Ammosov et al., 1957; Schapiro and Gray, 1960). However, such a classification of coal reactive and inert constituents is not applicable to all coals. In particular, the division of the amount of semifusinite acting as reactive or inert is controversial, as shown by Steyn and Smith (1977). An explanation for this discrepancy is that the composition of macerals and, hence, the technological behaviour of these macerals may differ from region to region because of different coalification and depositional conditions. In recognition of this, Benedict et al. (1968a) considered the same breakdown for semi fusinite plus other inertinite macerals of low reflectance, while other authors used little or no semi fusinite in their reactives Brown et al., (1964); or relatively large and variable amounts Steyn and Smith, (1977).

More details on the development on coal petrology (classifications and behaviour of maceral groups and microlithotypes and its application to coke making) have been published in a number of excellent reviews Stach et al., (1982); Falcon and Snyman, (1986).

Based on the maceral behaviour during carbonisation (reactive and inert), i.e. the concept that is used today for explaining coal carbonisation behaviour, several mathematical models have been developed to predict coke strength. Each model seems to estimate with a high degree of accuracy when applied to coals which are more or less similar in petrographic composition to the coals for which the model was developed.

Two models were developed in USA based on petrographic data for the prediction of coke strength and the formulation of coking blends, one developed by United States Steel and the other by Bethlehem Steel. The US Steel model for ASTM coke stability was firstly designed by Schapiro et al. (1961) and based on the earlier Russian work of Ammosov et al. (1957). Schapiro et al. (1961) modified this model and applied it to coals used by US Steel for the prediction of the ASTM stability factor.

The US Steel model is the basis for predicting coke quality from specific coals. The reactive coal components comprise all of the vitrinite and liptinite and one-third of the semi-fusinite, while the inerts include the remaining two-thirds of the semifusinite, together with the remaining inertinite and mineral matter. This model requires data from the maceral and reflectance analyses in which the reflectance of all the reactive and semi-inert macerals are measured, as well as the calculation of mineral matter of coal (MM). Reactive macerals are further subdivided into 21 ranges of 0.1% reflectance (V-type). From petrographic data and coke strength values, different curves can be plotted: (a) the optimum ratio of reactives to inerts (R/I) for each V- type; (b) the variation of the strength index (SI) with the quantity of inerts for various V-types; and (c) the variation of the strength index with the composition balance index (CBI) for various stability factors. The optimum inert ratio was established by physically isolating each of the macerals and determining, by means of micro-coking tests, what ratio gave the maximum strength value. With higher or lower proportions of inerts than the optimum, the coke strength decreases. The other indices defined by these authors are: a composition balance index (CBI) and a strength index (SI), the latter also being referred to as a rank index. CBI is the ratio of inert components in coal to the optimum ratio of reactive to inert that a coal of a given rank should have. When for a given coal the optimum CBI is equal to 1, the best coke is obtained. The strength index (SI) can be evaluated to determine the relative coke strength made from coals of different ranks and types.

An advantage claimed for this model is that both indices, CBI and SI, are additive and it should be possible to use petrographic assessments without pilot coke oven tests. The US Steel model gave fully satisfactory results for the low semifusinite Appalachian coals and blends for which the system was developed. However, this model is based on correlations of test-coke data with the petrographic composition of the coals being carbonised, keeping the test conditions constant. The restrictions of this model are that it, as is the case with so many other models, is only truly valid if the same sets of pilot scale conditions are followed.

A petrographic model has been adapted to select coals not having excessive coking pressures. (Benedict and Thompson, 1976). Some low-volatile coals, especially those with vitrinite reflectance >1.65% and of low inert content, produce excessively high wall pressures during carbonisation. In normal industrial practice, these low-volatile coals are never coked singly and are normally used as a 25–30% component in coal blends. These authors showed that both, vitrinite reflectance and maceral composition of coal could be related to excessive pressures during carbonisation.

The coke strength prediction model of Brown et al. (1964) differs from those already described in the subdivision of semifusinite. They considered that ‘‘virtually all semi-fusinite remains unchanged during carbonisation. The predominant inert character of semi-fusinite was first noted by Taylor (1957) who concluded, ‘‘semifusinite may be distorted and altered in its chemical nature, but that no appreciable amount fuses and enters the fused coke structure’’. Taylor et al. (1967) , in an interlaboratory study, provided evidence of the inert role of semifusinite using a range from low volatile to high volatile bituminous coals. They also suggested that transitional material between vitrinite and semifusinite became weakly plastic during heating and that it should be included in the category of vitrinite. Consequently, they suggested that, as a rule, semifusinite with a reflectance higher than 0.1 to 0.2 compared with the mean reflectance of vitrinite in the same coal is inert. Other authors argued that the inert character of the semifusinite could be a result of the small laboratory scale test oven, used in the carbonization tests. In coking conditions, the semifusinite could be much more interactive.

On the other hand, when Cretaceous coals from Western Canada, with a higher proportion of semi-fusinite than Carboniferous coals, were used, the model of Schapiro et al. (1961) predicted coke strength values lower than those measured experimentally. To get satisfactory coke strength prediction using coals with a total semi fusinite content greater than 20%, a modification based on the assumption that semifusinite makes a greater contribution to the reactive components was made Carr and Jorgensen (1975). These authors decided that half of the semi-fusinite is effectively a reactive component. However, no evidence was found to support this assumption. The work of Nandi and Montgomery (1975) on the nature and thermal behaviour of semi-fusinite in such coals using a hot-stage microscope provided useful data. They concluded that high-reflectance semifusinite is a totally inert component during carbonisation (no signs of melting or softening were observed at 450 ^{o}C), while low-reflectance semi fusinite was reactive, similar to vitrinite, its melting point being about 85 ^{o}C lower than that of the corresponding vitrinite. Pure vitrinite melted at a temperature of 420 ^{o}C.

Based on these conclusions, other models developed which Pearson and Price (1985) proposed the use of a ''cut-off'' reflectance or reactive ''cut-off'' value (Rcut-off) that separates reactive and inert macerals in a random reflectogram of all coal macerals. A good correlation between maximum vitrinite reflectance and Rcut-off for 76 coals ranging from 0.89% to 1.63% (RoV_{max}) was found ($r^2 = 0.92$). For a given coal, the new parameter can be deduced from the correlation between RoV_{max} and Rcut-off.

Recently, the proportion of semi fusinite as a reactive component, in the range of 33–50%, has been determined by coke microscopy. The proportion varies from coal to coal and 50% of the reactive semifusinite is recommended for Western Canadian coals when coal petrography is used to predict coke strength for blends. Associated problem, however, is to explain the low rheological values for Western Canadian coals. The rheological values cannot be compared to other similar rank coals (Australian or US Carboniferous coking coals) and, therefore, they should not be directly used in calculations of average fluidities of blends containing coals from many sources. High quality coke can be produced from Canadian coals with maximum fluidities in the range of 3–10 ddpm. These values strongly differ from the minimum value of maximum fluidity (100–200 ddpm). Despite the development listed above, it was concluded that the most satisfactory evaluation of the influence of such coals in blends made with coals from other sources is the use of pilot-scale carbonisation tests.

Other models to predict coke strength do not exclusively use coal petrography and utilize the dilatation characteristic of coals and blends using a Ruhr or Audibert-Arnu dilatometer. The model devised by Mackowsky and Simonis (1969) in Germany provides not only a basis for prediction of the MICUM strength and abrasion indices (M40 and M10) for cokes produced from a range of Ruhr coals and blends, but it also predicts yields of carbonisation products (coke, gas, liquid byproducts and tar). In addition to coal composition parameters, this model takes into account coking conditions, that is, coal size of the charge, bulk density, coking rate, mean oven width, and coking time.

In this model, the MICUM M40 index (wt.% of coke, >40 mm after 100 revolutions) is expressed as:

$$M40 = aK + b + dMs$$

Where K is a factor including the coking conditions as a function of the bulk density, oven width and coking time; Ms is the particle size content of the coal; b is a rank factor; and a and d are coefficients based on volatile matter and a parameter named G-factor.

The G-factor is usually obtained from parameters derived from the Ruhr dilatometer test, which is a modification of the Audibert-Arnu dilatometer test (the softening and resolidification temperatures and the percentage of coal contraction and dilatation). Although the G-factor is considered additive for coal blends, there is a limitation for blends composed of coals whose plastic range does not overlap sufficiently. Experiments on the behaviour of the different maceral groups in this dilatometer showed that it was also possible to calculate the G-factor for a given coal from its petrographic composition.

The prediction model for M40 and M10 indices (wt.% of coke >40 mm and < 10 mm in size, respectively, after 100 revolutions) can only be applied to a certain range of coals characterised by volatile matter contents between 18 and 35 wt.% daf and inert contents below 20%, this being very restrictive.

The model developed by Nippon Kokan (NKK) in Japan can be seen as a coal property ‘‘window model’’, where the blending ratio is determined such that the maximum vitrinite reflectance and maximum fluidity of the coal blend falls within an established optimum range ‘‘window’’. If the coal blend characteristics fall inside this window, the resulting coke will be of acceptable quality for their blast furnaces use. Within the framework of this model, desirable properties of a coal blend range of RoV 1.2–1.3% and a Gieseler maximum fluidity between 200 and 1000 ddpm. The coal blends must meet these specifications if the target coke strength index of higher than 92.0 (JIS DI30/15, wt.% of 15 mm coke after 30 revolutions) is to be obtained.

However, blends located outside of the optimum window also gave high quality coke indices Poos (1987). For the coal blends studied, other prediction models do not work satisfactorily. The CRM (Cente de Recherches Metallurgiques in Belgium) has developed a coke strength prediction model based on three parameters: (a) the inert content of coal, (b) the reactive caking index, and (c) the maximum fluidity. The reactive caking index was defined as a function of vitrinite reflectance. Formulae have been developed for calculating each of these parameters for blends from the values of the individual coals carbonised in a 300-kg pilot oven.

The Coal Research Establishment in UK established a target specification for the blending of high and low-volatile coals based on total dilatation and volatile matter content. (Gibson and Gregory 1978). It is recognised that these two parameters, generally, are not sufficient in themselves. In addition, it is necessary to consider the size distribution of the mineral matter associated with the coal and the compatibility of blend components.

In summary, because of the fundamental research work done by a variety of researchers, the prediction models of coke strength has expanded considerably. Highlighting that coke quality parameters are strongly dependent on coal properties, efforts were focused on the use of petrographic and rheological properties. With regard to the single coal and coal blends used, one prediction model can be no better than any other model, for, as the saying goes "no model is right but any model is better than nothing". This implies that any model is right within the spectrum and conditions in which it was developed, but great care must be taken not to rely on it when coals from widely different sources are used in developing the model.

This fact is observed by other researchers (Valia H.S. 1989), which tried to compare different prediction models. This resulted in the Inland Steel Companies own prediction model and as the other have merit only to the coals used to create the model. However Valia introduced the concept of relating the coking range, which is the amount of deg Celsius when the softening temperature are subtracted form the resolidification temperatures as determined by Gieseler plastometer. He also established that the ash composition plays a major roll in the quality of coke which was quantified by a Alkali Index, However samples contaminated with blast furnace slag was used as a base of describing this finding, which makes the assumption the mineral matter in the coal is the same as that reported in the ash composition analysis. The model proposed by Valia holds merit but at Mittal South Africa the same R2 could not be obtained hence it was not used in the prediction of CSR.

All of this brings the coke producer back to the question "How to select coals for quality coke"?

To start to answer this question, it is necessary to first look at coal, what it is, how it developed and how to evaluate the differences between those from widely different sources.

Coal is a readily combustible rock containing (but not limited to) more than 50% by weight or 70% by volume carbonaceous material. It is formed from altered plant remains which are compacted, over time and exposed to temperature and burial. Coal can be characterised by assessing: (a) microscopic constituents, including macerals, mineral matter and microlithotypes, (b) rank and the macroscopic constituents such as sapropelic coals and humic coals.

This approach is explained by Falcon and Snyman (1986), and shows that coal properties such as the above are influenced by specific plant matter when originally deposited, the climate environment, and any catastrophic events that occurred either at the time of deposition or thereafter. It brings into context that no two coals are exactly alike and that when choosing or selecting a coal for any given technology a thorough characterisation of the coal should be undertaken first. It is necessary to understand the coal and its inherent properties or building blocks before using or evaluating it for a technological process. As was seen above coal properties dictate the properties of the coke and the behaviour of the coal in the coking process.

This study will show the fundamental rules to be followed in selecting coals for coking, it will also try to explain some anomalies arising from our understanding of the process of transforming coal to coke.

METHODOLOGY

1.3 Sampling

The samples used in this report were part of a test program conducted by Mittal Steel South Africa in 2005 and 2006. The aim of the test programme was to identify suitable coals which could be added to the current blend or to make up a new cost effective blend with the same or better coke properties.

The coal samples were all received from the mines in two three ton sample blocks split between the Vanderbijlpark and Newcastle testing facilities. The coal and single cokes produced from these coals are subdivided in to three major groups by geographical origin: South Africa (two coals), Australia (two coals) and United States thirteen coals.

All coal samples were sampled at their respective mines. After beneficiation the samples were collected over a 5 day period in accordance with ISO 13909 (Hard coal and Coke sampling – Mechanical Sampling). On receiving the coal samples Advanced Coal Technology Laboratories in Pretoria (ACT) sampled the three ton samples in accordance to ISO 18283 (Hard coal and coke sampling – Manual Sampling). ACT laboratory was also responsible for all the analytical work done on the samples; namely proximate analysis, ultimate analysis, physical analysis, rheological analysis and petrographic analysis, in accordance with the respective ISO standards. ACT is an ISO accredited laboratory.

The cokes produced from these coals were produced in a 400 kg moveable wall pilot oven. The oven has two doors, like an industrial oven, and one chargehole at the top. The length between the doors is 1 m, the height of the charge is 1,05 m, and the width is 350 mm. Each of the two walls has seven electrical heating elements and three holes for thermocouples. The coke was sampled by the pilot plant personnel by screening the total amount of coke into the following size fractions: -125 + 100mm, -100 + 80mm, -80 + 63mm, -63 + 40mm, -40 + 35mm, -35 + 20mm, -20 + 10mm and -10mm. After all the coke was screened the representative sample was made up by calculating the ratios of respective sizes to make up a 1kg sample. This sample was used for the chemical, proximate and coke petrographic analysis. For other physical tests, e.g. the MICUM and IRSID tests the samples were taken from the respective size fractions stipulated in the test procedure (the test procedures will be elaborated on in Analytical Methodology). For coke petrography a 200g sample was split by the Mittal Steel laboratory and submitted to Petrographics SA, an Accredited Member of the International Committee for Coal and Organic Petrology (ICCP).

1.4 Analyses and Tests

1.2.1 Coal

The following chemical and physical tests were conducted on each coal sample:

1.4.1.1 Moisture (air dry base) ISO 331:1983

Air-dried moisture as determined by the short analysis is affected by the ambient atmospheric conditions. Conditioning of the sample is essential to obtain repeatable results. It must be understood that moisture released under these test condition (105-110°C) as air-dried moisture is not necessarily associated with the coal matter. Some clay minerals may contain absorbed moisture which might or might not be released under the test temperature range. This can be detrimental, if the moisture is only emitted under higher temperatures and this will then influence the volatile matter content and especially when used as an indicator of the coal's rank. To avoid this error the mineral matter needs to be taken into account.

1.4.1.2 Volatile Matter ISO 562:1998

Volatile matter is the gas and liquid products resulting from the thermal decomposition of coal. The yield of volatile matter depends on the conditions of heating, particularly the temperature.

The volatile matter content is of importance in that it relates to the swelling properties in coking coals. It is also used to calculate the coke yield in the coking process, once all the volatile matter has been driven off.

1.4.1.3 Ash ISO 1171: 1997

Coal itself does not contain ash. Ash is the remnant of mineral matter in coal once it has undergone combustion. The ash is approximately 90% of the mineral matter due to the thermal decomposition and the emission of inorganic gases from the mineral matter.

1.4.1.4 Fixed Carbon

The solid remains after the determination of the volatile matter is the whole of the mineral matter and the non-volatile matter in the coal. The non-volatile organic matter is termed "fixed carbon". In the proximate analysis, this value is determined by subtracting the total of the percentage moisture, volatile matter and ash from a hundred. The proximate analysis results are all reported on air-dried basis but can be converted to other basis by applying the relevant conversion methods.

1.4.1.5 Sulphur ISO 334:1992 / 351:1996

Sulphur occurs in coal in three forms: 1) sulphide or pyritic sulphur, 2) sulphate sulphur and 3) as organic sulphur.

First the total sulphur is determined by the traditional method or by other more sophisticated equipment.

The pyritic sulphur is determined by digestion of the coal sample in nitric acid to decompose the pyrite. Once in solution the determination is done by visible light spectrophotometry.

The sulphate sulphur is determined by leaching it out with hydrochloric acid and precipitated and weighed. The organic sulphur is then determined by difference between the sum of the sulphate and pyritic sulphur and the total sulphur.

1.4.1.6 Elemental analysis

Analyses for the elemental constituents of coal, Hydrogen, Oxygen, Nitrogen.

1.4.1.7 Free Swell index ISO 501

The crucible swelling number is one of the most generally used tests to determine if a coal has coking potential. It permits quick classification of coals having mediocre or average coking properties, but makes hardly any distinction between good and bad coking coals. These tests are merely an indicative parameter. Most coals will swell and start to evolve volatile matter to some extent when brought in contact with heat. The swelling index can be used as a quality control parameter that can give an indication to whether or not the sample has been oxidized. With extensive oxidation the tendency of the coal to swell will be hampered. There are, however, coals with good swelling indices that cannot be used in coke making. These tests also do not incorporate the micro porosity of the coal and thus do not reflect the true nature of a coal’s coking ability.

1.4.1.8 Roga index ISO 335:1974

This tests the caking power of the coal, but as in the case of the swelling index, Roga is also just indicative and Roga values can differ greatly from laboratory to laboratory. The Roga test is a simple inexpensive test and does not require sophisticated equipment. Roga values also only indicate the possible caking power of coal and as such they do not quantify the coking ability. Roga tests are used to do routine quality control but care must be taken in using Roga values to identify good coking coals

1.4.1.9 Dilatation (Dilatometer) ISO 349:1975

Dilatation is a test whereby freshly ground coal is wetted and formed into a pencil 60mm long. The pencil is placed in a tub and a sliding-fit steel rod placed over it. The tub is placed in a special furnace at 300°C and heated at 3°C/min. It must be brought to mind that dilatation is only one aspect to consider and it is possible for a coal to have bad dilatation characteristics but still perform reasonably well as a coke feedstock due to the other parameters. This anomaly could be the result of different maceral compositions and the ratio of "optimum inerts" versus the "total reactives" thereby making up the Composition balance.

The mechanism of dilatation is not well described in literature and is being referred to as a phenomenon. There is however a link between dilatation and rank, this link only exists for northern hemisphere coals which have a higher vitrinite content. The dilemma in the southern hemisphere coals is the occurrence of what is called semi-reactive fusinite (which will be described later in the petrography section). Such forms of fusinite are likely to be the reason why we cannot find a link between rank and dilatation in Gondwana coals. This maceral group appears to be transitional between vitrinite and inertinite. If heated above 600°C, it often results in isotropic coke unlike the anisotropic coke formed by vitrinite.

The micro texture of the fusinite the truly inert organic maceral might also explain to some extent why some South African coals show poor dilatation but still produce reasonably good quality coke. If we were to assume that swelling of coal is due to the tar distillates not being able to escape when vitrinite undergoes deformation or plasticity for a given rank (and that the semi-reactive fusinite also reacts in a similar way), then it may be expected that the fusinite will not dilate because the tar is not hampered and can escape due to the micro structure of fusinite. The semi-reactive fusinite will however still become plastic after the tars have escaped and will form an isotropic coke and not an anisotropic coke. This implies that the dilatation value used to select coal for coking on the Gondwana coals will be distorted and that the value will not reflect the real coking capability of a particular coal. Reasonably good coking coals might be discarded due to this shortcoming.

1.4.1.10 Gieseler Fluidity

This test measures the plasticity of the coal and at what temperature the maximum fluidity is achieved. Five grams of freshly ground coal (< 0,4mm) is placed into a crucible by pressing it with a 1 kg weight ten times. The test starts at 350°C and is heated at a rate of 3°C/min. The stirrer that will stir the coal is driven with a constant torque. The stirrer's revolutions are measured on a dial and reported as dial divisions per minute (ddpm). As the vitrinite starts to enter the plastic zone the ddpm values will start to increase due to the experiencing of less friction when the coal becomes more fluid.

The initial temperature of softening is recorded when the dial reads 1ddpm and when the dial reaches its maximum reading the temperature is reported as maximum fluidity temperature. When the dial reaches zero it is reported as temperature of solidification.

These values are important when deciding which coal to use in a blend for coke production. If coals are chosen that will solidify before the other coals are soft (in their plastic zone) they will not form good coke. The temperatures of initial softening and solidification should overlap.

The maximum fluidity value is an indication of the coal's capability to mix, bond and bind with the other coals in the blend. This characteristic of the coal is related to the rank and the maceral composition (the ratio of vitrinite to inertinite). The more vitrinite present at certain ranks (1.2 to 1.5) the higher the fluidity. As in the dilatation test, it is not only the vitrinite that plays a role in this test, but also the reactive semifusinite. Irregularities in this test can crop up with the sample just forming a ball in the crucible and hence the stirrer will not see any resistance and deliver abnormally high values that can be misleading. More anomalies can be caused not only by the fusinite but also where there is an absence of exinite due to the coal being slightly heat affected. This is very prone to occur in South African coking coals due to the fact that most of this country's coking coals were artificially heated geologically and therefore underwent an increase in rank due to dolerites sills. With this artificial increase in rank most if not all of the exinite has been de-volatilized. It is believed that when exinite is heated it yields high amounts of tar and solvents. It is also believed that these solvents play a major role in vitrinite becoming plastic and fluid in the temperature range 350^{o}C to 450^{o}C. Thus if there are no exinites in a coal, the solvents need to come from the vitrinite which might take longer and would definitely be lower in proportion than that in exinite. This might then be an explanation why some of our coals do not fluidize with the test parameters of the Gieseler plastometer. These anomalies, including the case of dilatation, have often resulted in coals being discarded by coke makers as weak coking coals as a result of a test which was developed for Northern hemisphere coals and which was not capable of distinguishing between the differences of northern and southern hemisphere coals.

1.4.1.11 Ash Constituents

The constituents in the ash are the oxides of the minerals that are present in coal, provided that the combustion of the coal was done under full oxidizing conditions.

The classical means of determining the ash constituents is to subject the ash to wet chemical analysis. More recently X-Ray Fluorescence and neutron activation analysis have been utilized for the determination of these inorganic ash components.

The ash constituents have a significant impact on the uses of the specific coal and the process equipment that could be used. For instance the ratio of acid to base oxides and the CaO, MgO and Fe_2O_3 have major effects on the ash fusion temperature.

1.4.1.12 Ash Fusion Temperatures

To determine the ash fusion temperature a pyramid made from the ash of the coal is placed in a furnace. The temperature is raised to the point where the ash melts; the temperature is noted and then increased. The temperature is constantly increased up to where the pyramid becomes fluid. Again the temperature is noted.

The ash fusion temperature is fairly important in both steam coal and coking coal operation. It gives an indication as to whether the specific coal will start to clinker in boilers and fuse to coke oven walls.

1.4.1.13 Petrographic Analysis

Petrographic analysis is the determination of the microscopic organic building blocks of coal, which was formed from the original plant tissues that accumulated as peat, were decomposed, and finally coalified. These building blocks are called “Macerals”. Macerals are divided into three broad groups; Vitrinite, Exinite (Liptinite) and Inertinite. The ratios of these maceral groups with respect to one another and the reflective intensity of the vitrinite group in particular, supply a definite fingerprint to each and every coal that will be unique in its own way.

From the ratio of vitrinite to inertinite, predictions can be made as to how a coal will combust, i.e. high vitrinite low inertinite will produce a better quality flame and burn out will occur much faster whereas high inertinite and low vitrinite coals will take longer to burn out and would require a higher temperature for ignition.

Using the same ratio it is also possible to predict the coking characteristics of a coal i.e. vitrinite forms the “cement” and inertinite the “aggregate” in a coke but because there is no one coal that could fulfil all the desired quality requirements for coke making blends, the latter are being made up of individual coals each with their own unique properties which contribute (either cement or aggregate or both) to the overall blend and ultimately to the quality of the final coke.

Maceral reflectance which is indicative of the rank or maturity of a coal is not only the most informative parameter in the coal, but it can be used to correlate or predict certain key physical and chemical properties of coal.

By using petrography the differences between Carboniferous coals from the northern hemisphere and the Gondwana coals form the southern hemisphere are easily identified. Northern coals are higher in vitrinite and lower in inertinite than their counterparts in the south.

1.4.1.14 The Maceral Groups

Three maceral groups form the foundation of petrography namely: vitrinite, exinite and inertinite [NB. whilst Liptonite is now the preferred terminology for Exinite, Exinite is used in this study in order to standardise with all current and past literature]. Each of these groups can be subdivided into more finely defined sub macerals, all of which share similar chemical and physical properties with in each group. For the purpose of this paper we will only refer to the three major group macerals.

3.2.1.14.1 Vitrinite

Vitrinite is formed from cell wall material and cell fillings of wood plant tissue (leaves, roots, branches and trunks). Vitrinite does not have a defined structure due to the process of gelification. This gelification happened mainly in anaerobic reducing conditions under water, meaning that the gelified peat was protected from biochemical alteration by oxidation.

3.2.1.14.2 Inertinite

Inertinite is formed from the same material as vitrinite but in this case little or no gelification took place and the peat was strongly altered by oxidizing conditions. This is mainly due to changes in the environment when peat accumulation took place. There might have been dry periods leaving the peat dry and open to oxidation. Inertinite has a much more structured appearance than vitrinite and is lighter (whiter) in colour due to the amount of dense orientated carbon molecules. Inertinite has a much wider variety of macro and micro structures than vitrinite, especially in the South African coals. It can range from very well structured porous forms to an almost undefined nonporous gelified structure closely resembling vitrinite. This undefined structure is called semi fusinite and a part of this is termed semi-reactive fusinite which, if heated above 600^{o}C forms isotropic coke unlike the anisotropic coke formed by vitrinite. This fusinite and the reactive part thereof is responsible for some of the least understood anomalies in coking coal characterisation and classification in South African and other Gondwana coals. It is also responsible for the difficulties when coals containing significant amounts of this maceral group are used.

3.2.1.14.3 Exinite

The term exinite is used to describe a chemically distinct group of plant parts such as fossil algae, spores, cuticles and resins. This maceral group contains the highest amount of volatile matter of all the macerals. It produces waxes, fats and oils and is the darkest in colour when viewed through a petrographic microscope. But very little of this maceral group occurs in South African coals.

1.4.1.15 Analytical Techniques

Preparations of a petrographic block ISO 7404-2

Representative air-dried sample of coal is crushed to and upper size of 1 mm. A15 g portion is mixed with a binder and formed into a particulate block. One face of the block is ground and polished to provide a suitable surface for reflectance microscopy under oil immersion using reflected light.

The polished surface should be flat and free from scratches and relief. The surface area should be at least 600 mm2. The coal particles must be evenly distributed and make up at least 60% of the polished cross-sectional area of the block.

Maceral analysis (% by volume) ISO 7404-3

The polished surface is examined under oil immersion using a reflected light microscopy with a total magnification of between 250 and 500. The maceral groups are distinguished by their relative reflectance, morphology, colour, shape, size and polishing hardness.

The proportions of the individual macerals are determined by point count technique. Traverses are made at 0.5 mm intervals across the polished surface of the block. The material lying under the intersection of the crossline in the eyepiece of the microscope is identified and the point is counted. An automatic point counter is used to record 500 points on coal and to calculate the percentage of each component at the end of the analysis. The results are expressed as a percentage by volume to the nearest integer.

For technological purposes it is generally only necessary to differentiate between the three maceral groups. When using Gondwana coals however where inertinite-rich coals are common it is accepted that the reactive semifusinite should also be distinguished.

Reflectance measurements ISO 7404-5

The percentage of monochromatic green light with a wavelength of 546 nm which is reflected from an area of well polished vitrinite is compared with that reflected under the same conditions from a standard known reflectance. 100 readings are usually taken on different vitrinite particles evenly distributed over the polished surface of the block. The results are expressed as a mean reflectance value and also in the form of a reflectogram which shows the vitrinite-class distribution.

The reflectance distribution can provide valuable information about the rank of the coals whether the sample is made up of a mixture or blend of two or more coals of different rank or the coals contains heat affected materials. This method can also be used to explain why coking coals with the same volatile matter content can show wide variations in coking power.

With the increase in coalification, molecular changes in the structure of vitrinite give rise to changes in optical properties and thus increase reflectance.

1.2.2 Coke

1.4.2.1 Proximate analysis

% Moisture (adb) ISO 678: 1974
Same as for coal and used to calculate all the other values to the same basis.

% Ash (db) ISO 1171:1981
See Coal analytical.

% Volatile Matter (db) ISO 562:1981
See coal analytical.

% Sulphur
Coke contains sulphur originating mainly from the decomposition of pyrite and sulphur bonded to the three dimensional carbon network, which originates mainly from the organic sulphur in the coal but which can also be formed from pyritic sulphur. For coke utilisation there is not much benefit in distinguishing between these two kinds and the measurement of total sulphur is sufficient.

The sulphur content of coke has a considerable effect on the quality of the hot metal and slag. It is therefore a very important quality index, but there is hardly any means of regulating it, except by choice of coals. As sulphur in coal is distributed between the organic matter and ash, relatively extensive washing such as coking coals generally undergo tends to reduce the sulphur content. Some of the sulphur in the coal escapes with the volatiles, so that 50 to 60% of the sulphur remains in the coke. Taking into account the carbonisation yield, the sulphur content of the coke is thus slightly less than that of the coal.

1.4.2.2 Coke reactivity

As coke reactivity is one of the most valued parameters in coke, this section will start with a definition of coke reactivity.

When coke is placed at a high temperature in contact with an oxidising agent such as carbon dioxide or a metal oxide, the coke is said to be more or less reactive depending on whether the reaction occurs faster or slower or more or less readily. If this definition is imprecise, it is because the concept of reactivity is not precise in the mind of many coke users.

It is always possible to define precisely the reactivity of a coke for a given reaction with a known mechanism and under conditions that are also given. This holds for example, in the measurement of reactivity to carbon dioxide by one of the laboratory methods that will be described later. One is then able to classify different cokes in an order of increasing "reactivity" with which users are more or less in agreement. However, the problem is not necessarily resolved even then, since it is not known exactly what the relation is between the reactivity measured in this way and the behaviour of the coke in a full scale industrial plant. For example, it is fairly well established that in a foundry cupola the coke lumps react only at their external surfaces and that the amount of coke lost by gasification reaction depends mainly on the mechanical breakdown during descent of the cupola. This considerably increases the surface areas in the case of a weak coke.

Of the various tests that can be undertaken the test followed in this research is the Japanese CSR (coke strength after reaction). In this test the mechanical degradation caused by gasification is measured, chemical attack being carried out for a constant time. The apparatus used is an electrical retort, there is however argument throughout the world on the exact dimensions of this retort which has resulted in ISO embarking on re-evaluating the test.

1.4.2.3 CSR & CRI ISO 18894

CRI (Coke reactivity index)

The Coke Reactivity Index is the percentage weight loss of coke after reaction with carbon dioxide to form carbon monoxide under the following conditions:

A test portion of dried coke sample having a size range from 19 mm to 22,4 mm is heated in a reaction vessel (electrical retort) to 1100 ^{o}C in a nitrogen atmosphere. For the test the atmosphere is changed to carbon dioxide for exactly 2 hours. After the 2 hours the sample is allowed to cool down to 50 ^{o}C in a nitrogen atmosphere. The comparison of the sample weight before and after the reaction determines the coke reactivity index (CRI).

CRI expressed as a percentage by mass:

$$CRI = 100 \times \frac{M_0 - M_1}{M_0}$$

Where M_0 is the mass in grams of the sample before reaction and M_1 is the mass in grams of the sample after reaction.

CSR (Coke strength after reaction index)

The Coke Strength after Reaction Index is the reacted coke formed in the CRI test. This is treated in a specially designed tumbler call an “I-tumble tube” which is a tube turning end over end so as to allow the coke particles to tumble form one end to the other, for 600 revolutions during 30 min. The CSR value is determined by sieving and weighing the amount of coke passing through either a 10,0 mm or a 9,5 mm sieve.

CSR expressed as a percentage by mass:

$$CSR = 100 \times \frac{M_2}{M_1}$$

Where M_2 is the mass in grams of the fraction of the sample >10,0 mm or >9,5 mm after tumbling, and M_1 is the mass in grams of the sample after reaction.

1.4.2.4 Coke Strength tests

3.2.2.4.1 MICUM

The micum is the oldest strength test. It consists of treating 50 kg coke not passing a round-hole sieve of 63 mm in a 1x1 m rotating drum making 100 revolutions in 4 mints and then sieving it. However the test performed at Mittal Steel South Africa is screened on a 30 mm round-hole sieve. The reason for this is that Mittal blast furnaces run on a high load of sinter and hence the size fraction has been reduced to simulate the coke being loaded. The same procedure is followed as described in the sampling section, i.e. a sample of 50 kg is made up proportionally from the sizes +30 mm upwards. There is also a good correlation between the Micum test done on a starting feed size of + 63 mm and those started on +30 mm feed size. The following indications can be found:

1. The micum 10 (or $M10/_{30}$) index, which is the residue below 10 mm and fairly well characterise the abrasion resistance of the coke.
2. The micum 40 (or $M40/_{30}$) index is the residue above 40 mm and which is regarded as an index of fissuring.

From comparative tests it may be concluded that coking plants that are thought to use the same standard actually perform the micum test in different ways and sometimes with different apparatuses. Under these conditions it is not surprising that one and the same coke shows different indices from one coking plant to another. It is therefore necessary to be very cautious in comparing results obtained from different coking plants.

3.2.2.4.2 IRSID Test

The IRSID test is performed with the same apparatus as the micum test. It differs essentially from that test in the following points:

1. The sample is taken on the round –hole sieve of 20 mm but at Mittal Steel a duplicate sample as made up for the micum test is used, so again a 50 kg sample is made up proportionally from the +30 mm size fraction up.

2. It is subjected to 500 rotations of the drum instead of 100.

3. Two indices are derived: the residue above 20 mm, called the I20 index, and that through 10 mm, called the I10 index. With respect to this study four indices were derived: I40/$_{30}$, I30/$_{30}$, I20/$_{30}$ and I 10/$_{30}$. The reason for this was purely to see if any anomalies could be detected or other anomalies explained.

3.2.2.4.3 Combination of Micum and IRSID tests.

The question is often posed whether the micum test could be replaced by the IRSID test. Their indisputable advantages and disadvantages are as follows:

1. The micum test provides two main pieces of information: it characterises the tendency of coke to fissure (M40) as well as its cohesiveness (M10). The IRSID tests characterise only cohesiveness, but this disadvantage disappears with relatively small cokes (Coke Quality and production).

2. The micum test and IRSID test are both conducted on similar proportionately made up samples, obtaining a size of coke + 30 mm which puts them on par with the current move to smaller coke size in the blast furnace. However they do characterise different properties of the coke with respect to is usage.

3.2.2.4.4 ASTM Stability and Hardness tests

These two tests were mainly conducted to check whether or not the data supplied by the American coal suppliers were correct.

Essentially this is the same test as the micum and IRSID, the drum dimensions is different (914 x 457 mm), the revolutions are different (1400 rev. at 24 rev/min.) and the screens are a square-hole screens (27 mm and 6.75 mm).

1.4.2.5 Coke Elemental analyses

The coke elemental analyses are mainly conducted to act as a check and to look at the alkalis. High concentrations of alkali metals in the blast furnace can damage the refractory lining.

1.4.2.6 Coke Petrographics

The purpose of this test is to establish the nature of the texture of the carbon in the binder phase of the coke. It is conducted microscopically.

A petrographic block of each sample was prepared in accordance with the ASTM Standard D 3997. The samples were then examined under the microscope.

250 random reflectance measurements were carried out over the surface of each sample block in accordance with the ISO Standard 7404 - 5, 1994, as far as possible on vitrinites or constituents derived from vitrinites, given that the samples contained thermally affected particles showing textural features.

Coke constituent analyses (petrographic composition and binder phase forms) were carried out according to the ASTM Standard D 5061 - 92. The carbon forms were distinguished on the basis of their reflectance, anisotropy, morphology and size.

The coke components were classified as follows:

3.2.2.6.1 Filler Phase Components

These filler phase components are derived mainly from those inertinite group macerals that do not soften appreciably during carbonization, and minerals.

Miscellaneous materials - these relate to the coke plant process and include depositional and additive carbons.

Increasing reflectance indicates increasing molecular ordering and "graphitization", which directly influences the performances of the materials as carbon reductants in metallurgical processes.

The performance of a coke is not only directly linked to the degree of “graphitization” as indicated by reflectance, but is also influenced by the differences in levels of molecular ordering of the different types of carbon forms.

3.2.2.6.2 Binder Phase Forms

These binder phase forms are produced from reactive coal macerals that soften during carbonization. Binder phase carbons consist of isotropic and incipient forms, and circular, lenticular and ribbon-like anisotropic domains.

The binder phase carbon forms originate from the reactive macerals of coking coals and have gone through a plastic phase during the coke making process. The binder phase literally binds together the filler forms into a cohesive, continuous material, promoting size stability.

The levels of molecular ordering of binder phase carbons are reported to be greater than those of filler carbons that have originated from inert parent coal macerals.

The type of binder textures in the coke are predominantly determined by the rank of the parent coal. The development of the coke textural forms is also influenced by the coking process itself (e.g. rate of heating).

Cokes from bituminous coals display varying degrees of anisotropy under the light microscope depending on the rank and reactive maceral content of the parent coal and the heating rate and temperature of carbonisation. A polarised reflected light microscope, fitted with an antiflex oil immersion objective, is used to quantify the carbon forms, which are classed according to shape, size and colour of isotropic and anisotropic domains observed in the coke.

Isotropic carbon (poorly ordered), displays similar optical properties in various positions when rotated at the microscope and viewed under polarised light, while anisotropic carbon (well ordered), has optical properties that vary upon rotation. Isotropic binder phase carbon is produced from poor to marginal coking high-volatile coals with vitrinite reflectance less than 0.8 %. Anisotropic forms are produced in medium volatile bituminous coals (1.1 - 1.7% reflectance). Isotropic carbon forms are observed again above 1.8 % reflectance (i.e. Medium Bituminous low-volatile coal). The reactive macerals form the binder phase of the coke, of all levels of coal rank while the inerts (inert semifusinite, fusinite, micrinite, macrinite and inertodentrinite) act as aggregate material. The inert macerals degasify, but remain essentially unchanged during carbonisation.

Studies in the literature showed that highly isotropic cokes have high gaseous (CO_2) reactivities. This is explained as being due to the structure being composed mainly of very thin cell walls and large pores resulting in a larger surface area for CO_2 to react with the carbon, whereas cokes from higher rank bituminous coals would contain thicker walls and fewer pores and less surface area. However, the main effect is probably due to isotropic coke being in fact anisotropic at submicroscopic level, thus possessing many more active sites for reaction with CO_2 than in cokes described as anisotropic (at macro-scale).

In the Blast Furnace, the CO_2 reactivity needs to be controlled, in order to limit coke consumption by solution loss in the bosh area of the furnace.

However, the reactivity should not be retarded to such an extent that there is only very little reaction by the time the charge reaches the hearth. Sufficient inertinite (filler) is also needed to give 'walls' enough strength for the blast furnace cokes. The ratio of the reactives to inerts in a coking coal is an important factor determining strength of the final carbonised product. Thus various coals (of different rank and vitrinite content), may be blended (sometimes even up to 27 different types as practised in Japan), to produce a coke with the desired properties.

In the submerged arc furnace, high CO_2 reactivity would also produce a similar high coke consumption rate at the top of the burden, due to the Boudouard reaction. The key issue again, as in the Blast Furnace is how low or high should the CO_2 reactivity be to obtain optimum smelting performance. Strength is not as critical in the submerged arc furnaces as in a blast furnace, thus cokes with higher reactives to inerts ratio may be tolerated.

Several .workers have observed that the coke produced from high volatile bituminous coals, which appears isotropic under the light microscope, is actually anisotropic at submicroscopic level. Such coke contains some submicroscopic ordered domains analogous to the microscopically observed mosaic units in coke from other coals. With increasing coal rank, the size of the mosaic units in the coke were reported to increase to the point of medium-volatile bituminous coals, where size reached a maximum. The vitrinite in low-volatile coal produced a coke having fine domains.

Abramski and Mackowsky (1952) showed that the microscopic texture of coke does not change significantly after solidification on heating up to 1500-1700°C and that the form and size of the domains persist, although the degree of anisotropy increases gradually with increasing temperature (graphitisation effect?). Taylor (1957) also observed in thermally altered coal in a seam, small spheres, initially of micron size in the isotropic "vitrinite". The spheres were observed to enlarge up to about the former solidification temperature at which they coalesced to produce the mosaic structure observed by other workers.

The following is a summary from unpublished confidential testwork undertaken by Suprachem for the purpose of establishing what transients during heating of coal in a coke oven.

Thus the transformation of coal during carbonisation to produce coke may be described as follows. Upon calcination at temperatures of 400-500°C the vitrinite material forms an isotropic pitch-like mass of plastic consistency (except for vitrinites of some low-volatile bituminous coals and anthracites). As the temperature rises, spheres (< 0.1 µm diameter) appear in the pitch-like mass. These grow larger with increasing temperature. The spheres appear to occur within the vitrinite, but never within the non-graphitising inertinite macerals. After replacing most of the plastic-material, the spheres begin to interfere with one another's further enlargement. Progressive increase in temperature leads to irregular shapes. At this point, a mosaic begins to form and the rest of the plastic material is converted to more spherical domains. Eventually all the isotropic pitch-like material is transformed into this anisotropic mesophase which solidifies into semicoke shortly afterwards. Further heating to 900-1000°C results in complete carbonisation and transformation into coke.

Initially when small, the spheres are mostly circular however deviations from sphericity begin to occur by either interference with one another, or as a result of the influence of a third phase, such as ash, which affects the interfacial tension. The chemical constitution of the pitch-like materials in which the spheres are formed is very complex. The > 10 000 chemical compounds present in the original pitch are believed to be mainly polynuclear aromatic hydrocarbons together with some oxygen- and nitrogen-containing compounds. Nucleation of the spheres is favoured by solid surfaces or insoluble particles that act as nucleation sites. These particles, however, do not become incorporated within the sphere. They aggregate around the surface of the sphere, causing it to have an irregular margin. In abundance, insolubles remain in the mosaic at the interstitial positions where spheres adjoin, forming a three-dimensional network through the coke, which is expected to affect the mechanical properties of the coke considerably.

Further testwork indicated that when finely divided natural graphite was added to the toluene-soluble fraction of a coke-oven pitch and carbonised, there was a marked association between mesophase and graphite orientation with pronounced orientation of the mesophase on the graphite surfaces.

The growth rate of the spheres appears to be dependent on temperature and time, with fewer and larger spheres formed at the lower rate of carbonisation. There appears to be a limiting temperature (around. 400°C) below which no spheres form, even over a 24-hour period. The higher the temperature, the shorter the time for complete conversion to mesophase, thus illustrating the strong influence of calcining conditions in a retort and coke-oven, in terms of final properties of the carbonised material for use in a given technology.

The formation of the mosaic begins with the coalescence of two spheres. After total conversion to mesophase, the material remains a viscous nematic liquid (presumably because it is in the form of a 'slurry'), that can be deformed by mechanical pressure. When held for long periods in this "liquid" condition, without interference from unconverted pitch, regions greater than 1 mm across having constant parallel orientation, have appeared. Clearly, the role of the pitch-mesophase interface in controlling the structure of the spheres and hence the final coke microstructure is most important

RESULTS

The results form the tests and analyses are presented in tabular form in Appendix 1.

In this chapter the results applicable to each specific coal will be presented, trends and observations with recommendations will be presented in Chapters 5, 6 and 7.

1.5 American Coals and Cokes

1.1.1 Twin Rock Coking Coal

The results in Table 1 Appendix 1 indicate a coal with some acceptable chemical properties, such as low ash content, high free swelling index and high Roga index. The sulphur content is high. The maceral composition of the sample exhibits a high vitrinite content of 85.9%, with subordinate amounts of reactive semifusinite, inert semifusinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderate volatile matter content is indicative of a medium rank coal, which is a typical “mid vol” coal according to ASTM and American coal publications. The vitrinite reflectance distribution varies from V-class 11 to 14, resulting in a mean maximum reflectance of vitrinite, RoV_{max} of 1.32%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV_{max} value, due to the small amount of reactive semifusinite in the sample. The total amount of reactives in the sample therefore comprises all the vitrinite plus only 0.4% reactive semifusinite, which results in a total amount of 86.3%. The total amount of inerts is 13.7%. This is less than the calculated amount of 19.5% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.70, which is significantly less than 1. This is indicative of a coal with a significantly high proportion of reactive macerals. The sample therefore exhibits excellent coking potential in terms of the predicted drum indices, which is confirmed by the high free swelling and Roga indices (9 and 88 respectively).

The rheological properties in Table 2 Appendix 1 exhibit excellent maximum dilatation and acceptable maximum fluidity, which will have a beneficial effect on coke quality. The ash composition exhibits an acceptable level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.2 Twin Rock Coke

The results in Table 11 Appendix 1 indicate a coke with a high binder phase of 80% and a filler phase of 20%, with only 3 % non-coking vitrinite and inorganic inerts corresponding to the low ash in the parent coal. The results in Table 14 indicate that the binder phase is predominately anisotropic (97%) and most of that material is "Lenticular leaflet" form. This is supported by the results in Table 17 Appendix 1 with the coke product having a low CRI of 20.5 and a reasonably high CSR of 67.5.

The cold strength of the coke product is within the expected range for a single component coke having a $M40/_{30}$ of over 70 and a $M10/_{30}$ below 8.5. The coke also produced a Stability Factor of 57 which, with the high CSR, is likely to make this coal component highly desirable in any blend in which it would be used. The petrographic rank of the coke shown in Figure 1 Appendix 1 shows a well graphitised coke with a reflectance distribution between 5.2 and 14.3 resulting in a mean reflectance of 7.93.

1.1.3 Knox Creek Coking Coal

The results in Table 1 Appendix 1 indicate a coal with medium ash content, low sulphur content, high free swelling index and high Roga index. The maceral composition exhibits a medium vitrinite content (58.1%) and a high amount of liptinite (8.1%). Reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The moderate amount of mineral matter is a reflection of the medium low ash content of the sample.

The relatively high volatile matter content is indicative of a moderately low rank coal. Here the high amount of liptinite contributes to the volatile matter content. The vitrinite reflectance distribution varies from V-class 7 to 11, resulting in a mean maximum reflectance of vitrinite, RoV_{max} of 0.98%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is higher than the RoV_{max} value, due to the full amount of reactive semifusinite being regarded as reactive material in the sample. The total amount of reactives in the sample therefore comprises all the vitrinite plus all the reactive semifusinite, which results in a total amount of 77.8%. The total amount of inerts is 22.2%, which is more than the calculated amount of 19.3% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 1.15, which is somewhat larger than 1, indicating a coal with a deficit in reactive macerals. The sample therefore exhibits moderate coking potential in terms of the predicted drum indices, which is confirmed by the high free swelling and Roga indices.

The rheological properties in Table 2 Appendix 1 exhibit good maximum dilatation and excellent maximum fluidity, which will have a beneficial effect on coke quality. The ash composition exhibits an acceptable level of phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are somewhat low, which could cause some problems during the coking process.

1.1.4 Knox Creek Coke

The results shown in Table 11 Appendix 1 indicate a coke with a somewhat lower binder phase (74%) and filler phase (26%) indicative of a low vitrinite coal. This is, however, much higher than would be expected for a coal with a vitrinite content of only 58.1%. The higher binder phase in the coke could be attributed to the 11.6 % reactive semifusinite and the high volatile matter which will result in less coke being produced from the coal but will show an increase in the coke parameters.

The results in Table 14 Appendix 1 show a high amount of isotropic binder phase (11%) with 29% incipient anisotropic and only 60% as anisotropic carbon forms. The major amount of the anisotropic carbon is located in the circular form which is indicative of a medium ranking coal. These forms tend to have a detrimental impact on the physical parameters of the cokes as is shown in Table 17 Appendix 1.

The coke produced has a reasonable $M40/_{30}$ index of 55.3. This is probably due to the reactive semifusinite although the $M10/_{30}$ index is on the limit at 11. The high coke CRI results shown in Table 17 Appendix 1 and the low CSR index 29.1 are indicative of a medium ranking coking coal. The low stability factor is a detrimental effect caused by the isotropic component in the binder phase as well as the anisotropic part being virtually entirely in the circular form.

In Figure 2 Appendix 2 the reflectance distribution of the coke is shown which has a distribution between 5.2 and 14.3 resulting in a mean reflectance of 7.45 indicating that the coal was well graphitised in the process.

1.1.5 Shoal Creek Coking Coal

The results in Table 1 Appendix 1 indicate a coal with a medium ash content, high free swelling index and high Roga index (8.5 and 87 respectively). The sulphur content is slightly high. The maceral composition of the sample exhibits a moderately high vitrinite content (76.1%). Reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite, micrinite and liptinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderate volatile matter content is indicative of a medium rank coal, which is a typical “mid vol”. The vitrinite reflectance distribution varies from V-class 10 to 13, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.22%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV (max) value, due to the small amount of reactive semifusinite in the sample. The total amount of reactives in the sample therefore comprises all the vitrinite, plus the small amount of liptinite, plus only 3.8% reactive semifusinite. This results in a total amount of 81.0% reactives. The total amount of inerts is 19.0%, which is less than the calculated amount of 22.3% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.85, which is somewhat smaller than 1. This is indicative of a coal with an excess of reactive macerals. The sample therefore exhibits excellent coking potential in terms of the predicted drum indices, which is confirmed by the high free swelling and Roga indices.

The rheological properties in Table 2 Appendix 1 exhibit excellent maximum dilatation and acceptable maximum fluidity, which will have a beneficial effect on coke quality. The ash composition exhibits a slightly high level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.6 Shoal Creek Coke

The results shown in Table 11 Appendix 1 indicate a coke with a high binder phase (83 %) and a filler phase (17 %), all indicative of a coal with high reactives. The results in Table 14 show a very low isotropic content in the binder phase (1%) and high anisotropic content (99%), with most of the anisotropic binder phase being in the lenticular form (72%). These results are supported by the results shown in Table 17 with the coke having a high $M40/_{30}$ index of 79.2 low $M10/_{30}$ index of 6.5, low coke reactivity (21.9) and a high hot strength “CSR” (63.5).

The coke reflectance is shown in Figure 4 Appendix 2 which shows a reflectance distribution between 4.1 to14.8 with a mean reflectance of 7.8.

1.1.7 Arch Export Blend Coking Coal

The results in Table 1 Appendix 1 indicate a coal with some acceptable chemical properties, such as low ash content, high free swelling index and high Roga index (8 and 91 respectively). The sulphur content is slightly high. The maceral composition of the sample exhibits moderately high vitrinite content (67.3%) and a high liptinite content (9.5%). Reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The small amount of mineral matter is a reflection of the low ash content of the sample.

The relatively high volatile matter content is indicative of a moderately low rank coal, where the high amount of liptinite contributes to the volatile matter content. The vitrinite reflectance distribution varies from V-class 7 to 11, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 0.95%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is only slightly higher than the RoV (max) value, due to the full amount of reactive semifusinite being regarded as reactive material in the sample. The total amount of reactives in the sample therefore comprises all the vitrinite plus all the reactive semifusinite, which results in a total amount of 82.9%. The total amount of inerts is 17.1%, which is less than the calculated amount of 20.0% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.86, which is somewhat smaller than 1. This is indicative of a coal with an excess in reactive macerals. The sample therefore exhibits moderate coking potential in terms of the predicted drum indices, which is confirmed by the high free swelling and Roga indices.

The rheological properties in Table 2 Appendix 1 exhibit good maximum dilatation and good maximum fluidity, which will have a beneficial effect on coke quality. The ash composition exhibits an acceptable level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.8 Arch Export Coke

The results shown in Table 11 Appendix 1 indicates a coke with a somewhat lower binder phase (77%) and filler phase (22%) which is indicative of a medium vitrinite coal.

The results in Table 14 Appendix 1 show a high amount of the binder phase being isotropic (19%) and incipient anisotropic (38%) with only 43% as anisotropic carbon forms. All of the anisotropic carbon is located in the circular form which is indicative of a medium ranking coal. These forms tend to have a detrimental impact on the cokes physical parameters as is shown in Table 17 Appendix 1.

The coke produced has a low M40/$_{30}$ index of 45 and moderate M10/$_{30}$ index of 9.3. This is indicative of a medium ranking coking coal which produces high amounts of the isotropic binder phase. This however does not explain why the coke has a reasonable CRI value of 29.2 and CSR value of 55.7 as shown in Table 17 Appendix 1. There is not much difference between this coal and the Knox Greek coal except for a 10% difference in vitrinite and a difference in maximum fluidity. One reason could be that the carbon forms analysed as isotropic binder phase could be anisotropic at molecular level, this may explain the reasonably good reactivity values. The stability factor is also anomalous in that it has a very low value (24.5) indicating a coke produced from a coal with a lower rank and high amounts of isotropic binder phase combined with the anisotropic carbon in the circular form.

In Figure 3 Appendix 1 the reflectance distribution of the coke is shown which has a distribution between 6.1 and 8.8 resulting in a mean reflectance of 7.52 indicating that the coal was well graphitised in the process.

1.1.9 Oak Grove Coking Coal

The results in Table 3 Appendix 1 indicate a coal with some acceptable chemical properties, such as low ash and sulphur contents, high free swelling index and high Roga index (8 and 85 respectively). The maceral composition of the sample exhibits a moderately high vitrinite content of 68.6%, with subordinate amounts of reactive semifusinite, inert semifusinite and traces of fusinite, secretinite and micrinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The low volatile matter content is indicative of a high rank coal. The vitrinite reflectance distribution varies from V-class 13 to 16, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.46%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV (max) value, due to the fact that all the reactive semifusinite in the sample is regarded as inert. The total amount of reactives therefore comprises only the vitrinite present in the sample, which results in a total amount of 68.6%. The total amount of inerts is 31.4%, which is far more than the calculated amount of 8.1% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample (Steyn and Smith 1977).

The ratio of total inerts/optimum inerts results in a composition balance index of 3.88, which is significantly larger than 1. This is indicative of a coal with a significant deficit in reactive macerals. The high rank and large composition balance index cause some problems in terms of predicting the drum indices because these factors fall in an area on the correlation curves (Steyn and Smith 1977) where insufficient data was available for the construction of reliable correlation curves. Other available data, such as the free swelling and Roga indices are therefore used as indicators of coking potential. According to these two properties, fairly good coking potential can be expected from this type of coal.

The rheological properties in Table 4 Appendix 1 exhibit acceptable maximum dilatation but somewhat poor maximum fluidity. This is likely to have a possible detrimental effect on coke quality. The ash composition exhibits a slightly high level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.10 Oak Grove Coke

The results shown in Table 12 Appendix 1 indicate a coke with a lower binder phase (76%) and a filler phase of 24%. This is indicative of a low vitrinite content coal.

The results in Table 15 Appendix 1 show a low amount of the isotropic binder phase (1%) and 0% incipient anisotropic with 99% anisotropic carbon forms. The major amount of the anisotropic carbon is located in the lenticular form which is indicative of a high ranking coal. These forms tend to have a positive impact on the physical parameters of a coke as is shown in Table 17 Appendix 1.

The coke produced has a high $M40/_{30}$ index (78) and a low $M10/_{30}$ index (5.9). Indicative of a high ranking coking coal is the fact that the CRI result shown in Table 17 Appendix 1 is very low (17.3) with a high CSR index (76.6). This can also be attributed to the high anisotropic binder phase much of which is lenticular in form. The stability factor reflects the positive effect provided by the anisotropic component on the overall mechanical strength of the coke.

In Figure 7 Appendix 1 the reflectance distribution of the coke is shown. This has a distribution between 3.7 and 14.5 resulting in a mean reflectance of 7.88 indicating that the coal was well graphitised in the process.

1.1.11 Alpha Amfire Coking Coal

The results in Table 3 Appendix 1 indicate a coal with a low ash content, high free swelling index and high Roga index (9 and 82 respectively). The sulphur content is high. The maceral composition exhibits a high vitrinite content (85.0%), whereas reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The small amount of mineral matter is a reflection of the low ash content of the sample.

The low volatile matter content (19.2% db) is indicative of a high rank coal. The vitrinite reflectance distribution varies from V-class 13 to 18, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.58%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV (max) value, due to the fact that all the reactive semifusinite in the sample is regarded as inert. The total amount of reactives therefore comprises only vitrinite, which results in a total amount of 85.0%. The total amount of inerts is 15.0%, which is far more than the calculated amount of 5.1% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.
The ratio of total inerts/optimum inerts results in a composition balance index of 2.94, which is significantly larger than 1, indicating a coal with a deficit in reactive macerals. Coking potential cannot be predicted in terms of the drum indices due to insufficient correlation curves. The other properties, however, indicate that good coking potential can be expected from this type of coal.

The rheological properties in Table 4 Appendix 1 exhibit very poor maximum dilatation and maximum fluidity, which will have a detrimental effect on coke quality. The ash composition exhibits an acceptable level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are somewhat lower, probably due to the high iron content.

1.1.12 Alpha Amfire Coke

The results shown in Table 11 Appendix 1 indicate a coke with a low binder phase (71%) and a filler phase (26%) indicative of a low vitrinite coal. This is however not the case. The coal proved to have a high vitrinite content (85%). The explanation could be that there is un-reacted vitrinite, as indicated by the presence of 3% non-coking vitrinite and 16% inorganic inerts in the coke shown in Table 11 Appendix 1.

The results in Table 14 Appendix 1 show a low amount of the binder phase being isotropic (1%) and 0% as incipient anisotropic with 99% as anisotropic carbon forms. The major amount of the anisotropic carbon is located in the ribbon form which is indicative of a high ranking coal. The ribbon anisotropic carbon form tends to have the same detrimental effect as the isotropic carbon form on the coke reactivity which is evident from the results form Table 17 Appendix 1 were the CRI is high 47.7 and the CSR extremely low 17. These values on their own will give the impression that the parent coal is low in rank, but in fact it has a high rank. The high amount of inerts and the low Fluidity and Dilatation values, in all likelihood, resulted from a coke which graphitised but did not form large mesophases due to the lack of fluidity. However such results may also infer that the carbon form in the coke which was analysed as anisotropic is not really anisotropic at the molecular level. Alternatively, that the inert level in the coal may be just too high which could not be compensated for by the reactives in the coal hence the production of a poor quality coke.

The coke however has a high $M40/_{30}$ index of 79.2 and a low $M10/_{30}$ index of 6.9. This is expected from this rank of coal but not from a coke with such poor reactivities.

Figure 5 Appendix 1 presents the reflectance distribution of the coke. This has a distribution range between 3.3 and 14.9 resulting in a mean reflectance of 7.61, thereby indicating that the coal was well graphitised in the process but that there is some green coke which could be the result of bad isolation on the oven doors or a malfunctioning heating element. Of interest in the distribution of the reflectance of the coke is the fact that it is spread over a wide area indicating a relatively high proportion of partially reacted inert vitrinites. This is also indicative of why the coal did not produce a high fluidity or a good dilatation.

1.1.13 Kepler Low Vol Coking Coal

The results in Table 3 Appendix 1 indicate a coal with low ash and sulphur contents, a high free swelling index and a slightly lower Roga index (8 and 74 respectively). The maceral composition exhibits a high vitrinite content (81.0%), whereas reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The small amount of mineral matter is a reflection of the low ash content of the sample.

The low volatile matter content is indicative of a high rank coal. The vitrinite reflectance distribution varies from V-class 13 to 18, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.59%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV (max) value due to the fact that all the reactive semifusinite in the sample is regarded as inert. The total amount of reactives therefore comprises only vitrinite, which results in a total amount of 81.0%. The total amount of inerts is 19.0%, which is far more than the calculated amount of 5.0% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 3.80, which is significantly larger than 1, indicating a coal with a deficit in reactive macerals. Coking potential cannot be predicted in terms of the drum indices due to insufficient correlation curves. Other properties, however, indicate that fairly good coking potential can be expected from this type of coal.

The rheological properties in Table 4 Appendix 1 exhibit moderate maximum dilatation and poor maximum fluidity, which will have a detrimental effect on coke quality. The ash composition exhibits low phosphorus content, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.14 Kepler Coke

The results shown in Table 11 Appendix 1 indicate a coke with a moderate binder phase (75%) and a filler phase (24%) indicative of a low vitrinite coal This is however not the case as the coal was found to have a vitrinite content of 81%. The explanation may be that un-reacted vitrinite is present and that the reactive semifusinite is inert.

The results in Table 14 Appendix 1 show that there are no isotropic or incipient anisotropic phases present and that anisotropic form comprise 100%. The major amount of the anisotropic carbon is located in the ribbon form which is indicative of a high ranking coal. The ribbon anisotropic carbon form tends to have the same detrimental effect as the isotropic carbon form on the coke reactivity which is not evident from the results from Table 17 Appendix 1 where the CRI is low at 25.4 and the CSR moderately high at 65.4. This, however, is in line with what could be expected from a high ranking coal. However this could also be a case where that which is classified petrographicaly as isotropic is actually anisotropic at the molecular level. The level of ash probably also played a part in it.

The coke has a high $M40/_{30}$ index of 79.8 and a low $M10/_{30}$ index of 5.9 this is expected from this rank of coal but not from a coke with such a high composition balance in the coal.

Figure 6 Appendix 1 illustrates the reflectance distribution of the coke, which has a distribution between 4.8 and 14.8 resulting in a mean reflectance of 8.32. This indicates that the coal was well graphitised in the process and a large amount of order is present in the coke carbon forms, this could very well explain the low CRI and high CSR.

1.1.15 Blue Creek No.4 Coking Coal

The results in Table 5 Appendix 1 indicate a coal with some acceptable chemical properties, such as low ash and sulphur contents, high free swelling index and high Roga index (9 and 89 respectively). As far as the petrographic properties are concerned, the maceral composition of the sample exhibits a moderately high vitrinite content (82.6%), with subordinate amounts of liptinite, reactive semifusinite, inert semifusinite and traces of fusinite, secretinite and micrinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderate volatile matter content is indicative of a medium rank coal. The vitrinite reflectance distribution varies from V-class 9 to 12, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.13%. Although all the reactive semifusinite in the sample is regarded as reactive, the amount is too small to have any effect on the reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal. It is therefore similar to the RoV (max) value. The amount of reactives comprises all the vitrinite, liptinite and reactive semifusinite present in the sample, which totals 87.0%. The total amount of inerts is 13.0%, which is far less than the calculated amount of 24.9% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.52, which is significantly smaller than 1. This is indicative of a coal with a significant excess in reactive macerals. The coking potential is very good, which is supported by the excellent free swelling and Roga indices, predicted by the drum indices.

The rheological properties in Table 6 Appendix 1 exhibit excellent values for maximum dilatation and maximum fluidity, which will be beneficial for coke quality. The ash composition exhibits high phosphorus and alkali contents. The ash fusion temperatures are favourably high.

1.1.16 Blue Creek No.4 Coke

The results shown in Table 12 indicates a coke with a high binder phase (82%) and filler phase (18%) indicative of a high vitrinite coal, with a high percentage of reactives.

The results in Table 15 Appendix 1 show a low amount of the binder phase being isotropic 1% and 1% as incipient anisotropic with 98% as anisotropic carbon forms. The major amount of the anisotropic carbon is located in the circular form which is indicative of a lower ranking coal. The circular anisotropic carbon form tends to have a detrimental effect on the mechanical strength of the coke this statement is however not true in this case. This can be the result of the high fluidity of the coal and the high resolidification temperature, giving the mesophases a longer time and a less viscose environment to form in.

The results form Table 18 Appendix 1 indicates that the CRI is low at 21.7 and the CSR moderate at 66.5.

The coke has a high $M40/_{30}$ index of 75.8 and a low $M10/_{30}$ index of 6.3. This is expected form a coke with a high binder phase which is mostly anisotropic.

Figure 8 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.0 and 11.6 resulting in a mean reflectance of 7.56 indicating the coal was well graphitised in the process.

1.1.17 Blue Creek No.7 Coking Coal

The results in Table 5 Appendix 1 indicate a coal with low ash and sulphur contents, high free swelling index and high Roga index (9 and 89 respectively). Petrographic properties exhibit a maceral composition with moderately high vitrinite content of 78.0%, whereas reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The small amount of mineral matter is a reflection of the low ash content of the sample.

The low volatile matter content is indicative of a high rank coal. The vitrinite reflectance distribution varies from V-class 13 to 17, resulting in a mean maximum reflectance of vitrinite, RoV (max) of 1.48%. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is similar to the RoV (max) value, due to the fact that all the reactive semifusinite in the sample is regarded as inert. The total amount of reactives therefore comprises only vitrinite, which results in a total amount of 78.0%. The total amount of inerts is 22.0%, which is far more than the calculated amount of 7.8% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 2.82, which is significantly larger than 1, indicating a coal with a deficit in reactive macerals. The high rank and large composition balance index cause some problems with the prediction of the drum indices since it plots in an area on the correlation curves where insufficient data was available for the construction of reliable correlation curves. Other available data, such as the free swelling and Roga indices are therefore used as indicators of coking potential. According to these two properties, very good coking potential can be expected from this type of coal.

The rheological properties in Table 6 Appendix 1 exhibit good maximum dilatation but somewhat poor maximum fluidity, which will have some detrimental effect on coke quality. The ash composition exhibits an acceptable level for phosphorus, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.18 Blue Creek No.7 Coke

The results shown in Table 12 Appendix 1 indicate a coke with a high binder phase (80%) and filler phase (20%) indicative of a high vitrinite coal, with a high percentage of reactives.

The results in Table 15 Appendix 1 indicate that the binder phase has no isotropic or incipient anisotropic forms with 100% as anisotropic carbon forms. The anisotropic carbon is located in the lenticular and ribbon form which is indicative of a medium to high ranking coal. An example of the lenticular and ribbon forms is shown in Figure 1 Appendix 2. The two thirds one third split in the carbon forms resulted in a well balanced coke.

The results form Table 18, shows the CRI is low at 24.1 and the CSR moderate at 70.2.

The coke has a high $M40/_{30}$ index of 79 and a low $M10/_{30}$ index of 5.5 this is expected from a coke with a high binder phase which is mostly anisotropic.

Figure 9 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.2 and 14.7 resulting in a mean reflectance of 7.56 indicating that the coal was well graphitised in the process.

1.1.19 Pinnacle Coking Coal

The results in Table 5 Appendix 1 indicate a coal with low ash and slightly high sulphur contents, moderate free swelling index and moderate Roga index (7 and 74 respectively). The maceral composition exhibits a moderately high vitrinite content of 74.3%, whereas reactive semifusinite and inert semifusinite occur in subordinate amounts with trace amounts of fusinite, secretinite and micrinite. The small amount of mineral matter is a reflection of the low ash content of the sample.

The low volatile matter content is indicative of a high rank coal with a vitrinite reflectance distribution varying from V-class 14 to 18+. The maximum reflectance value measured was 2.0%, which is included in V-class 18+. The mean maximum reflectance of vitrinite, RoV (max), is 1.69%. The high rank material with reflectance higher than 1.89% exceeds the upper reactivity limit for vitrinite. This means that a small amount of vitrinite in the sample is regarded as inert. The reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal, is therefore slightly lower than the RoV (max) value. The total amount of reactives therefore comprises only vitrinite with a reflectance up to V-class 18, which results in a total amount of 71.4%. The total amount of inerts is 28.6%, which is far more than the calculated amount of 2.6% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 11.0, which is significantly larger than 1, indicating a coal with a massive deficit in reactive macerals. Coking potential cannot be predicted in terms of the drum indices due to insufficient correlation curves. Other properties, however, indicate that moderate coking potential can be expected from this type of coal.

The rheological properties in Table 6 Appendix 1 exhibit very poor maximum dilatation and maximum fluidity, which will have a detrimental effect on coke quality. The ash composition exhibits low phosphorus content, whereas the alkali content is slightly high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.20 Pinnacle Coke

The results shown in Table 12 Appendix 1 indicates a coke with a low binder phase (60%) and filler phase (40%) indicative of a lower vitrinite coal, with a lower percentage of reactives.

The results in Table 15 Appendix 1 show that the binder phase has no isotropic or incipient anisotropic forms but 100% anisotropic carbon forms. The major amount of the anisotropic carbon is located in the ribbon form which is indicative of a high ranking coal. An example of ribbon flow anisotropic carbon form is shown in Figure 2 Appendix 2. The ribbon anisotropic carbon form tends to have a detrimental effect on the mechanical strength of the coke and the reactivity of the coke. Ribbon form of carbon is normally associated with high ranking coals with high fluidity and good dilatations, but this is not the case with this coal. However the same argument can be used here, as to say that the carbon forms we see in the coke which is classified as anisotropic could very well be isotropic which would then explain the poor reactivity performance of the coke shown in Table 18 Appendix 1. It would seam unlikely that this coal could form large ribbon carbon forms with almost non excitant fluidity and maximum dilatation (4 ddpm and 5 Max Dilatation). The coking window (temperature of softening to temperature of resolidification) is very small, not allowing the creation of large highly viscous mesophases which will form highly ordered carbon forms. The rank of the coal is extremely high at 1.7 and therefore the macro anisotropic carbon forms may have already been present in the coal before it was carbonised.

The results form Table 18 Appendix 1 show the CRI is high at 33.1 and the CSR very low at 46.

The coke has a fairly high $M40/_{30}$ index of 69.4 and a low $M10/_{30}$ index of 8.5. These results do not clearly show the impact of low reactivity, however the stability factor does gives an indication to this.

Figure 10 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.1 and 14.9 resulting in a mean reflectance of 8.94 indicating that the coal was well graphitised in the process.

1.1.21 Marfolk Eagle Coking Coal

The results in Table 7 Appendix 1 indicate a coal with some acceptable chemical properties, such as low ash and slightly high sulphur contents, high free swelling index and high Roga index. As far as the petrographic properties are concerned, the maceral composition of the sample exhibits a moderately high vitrinite content (77.0%), with a fairly high amount of liptinite and subordinate amounts of reactive semifusinite, inert semifusinite and traces of fusinite, secretinite and micrinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderately high volatile matter content is indicative of a medium rank coal. The vitrinite reflectance distribution varies from V-class 8 to 12, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.09%. Although all the reactive semifusinite in the sample is regarded as reactive, the amount is somewhat lower and therefore may have a limited effect on the reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal. It is therefore almost similar to the RoV (max) value. The total amount of reactives comprises all the vitrinite, liptinite and reactive semifusinite present in the sample, a large proportion (85.7%) while the total amount of inerts is 14.3%. This is far less than the calculated amount of 23.5% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.61 which is significantly smaller than 1. This is indicative of a coal with a significant excess in reactive macerals. A very good coking potential, which is supported by the excellent free swelling and Roga indices, is predicted in terms of the drum indices.

The rheological properties in Table 8 Appendix 1 exhibit excellent values for maximum dilatation and maximum fluidity which will be beneficial for coke quality. The ash composition exhibits very low phosphorus content, whereas the alkali content is high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.22 Marfolk Eagle Coke

The results shown in Table 12 Appendix 1 indicates a coke with a reasonable binder phase (76%) and a filler phase (16%) indicative of a medium vitrinite coal, with a medium percentage of reactives. Although the coal has a high vitrinite content the vitrinite reflectance spread is over a wide range of V-classes probably resulting in some of the vitrinite falling out of the coking range and the high volatile matter content, hence the lower than expected binder phase.

The results in Table 15 Appendix 1 show that the binder phase has no isotropic or incipient anisotropic forms but 100% anisotropic carbon forms. The major amount of the anisotropic carbon is located in the circular form which is indicative of a lower ranking coal. The circular carbon form can affect the mechanical strength of the coke and the reactivity of the coke. However this circular carbon form falls in the medium range moving closer to the lenticular form hence the reason for the above expected reactivities and mechanical strengths. Shown in Table 18 the CRI is low at 21.6 and the CSR moderately high at 57.8.

The coke has a reasonable $M40/_{30}$ index of 63.6 and a low $M10/_{30}$ index of 8.1, which may be expected for this rank of coal.

Figure 13 Appendix 1 shows the reflectance distribution of the coke which ranges between 2.0 and 11.5 resulting in a mean reflectance of 7.13. This indicates that the coal was well graphitised in the process, but that the rank of the coal was too low for a degree of order to be reached.

1.1.23 Wells Coking Coal

The results in Table 7 Appendix indicate a coal with low ash and slightly high sulphur contents, high free swelling index and high Roga index (8.5 and 85 respectively). The maceral composition of the sample exhibits a moderately high vitrinite content (70.9%), with a large amount of liptinite and subordinate amounts of reactive semifusinite, inert semifusinite and traces of fusinite, secretinite and micrinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderately high volatile matter content is indicative of a medium rank coal, where the vitrinite reflectance distribution ranges between V-class 8 to 11, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.0%. Although all the reactive semifusinite in the sample is regarded as reactive, the amount is somewhat diminutive to have any significant effect on the reflectance parameter RoR. This is indicative of the rank of the total amount of reactives in the coal. It is therefore only to some extent higher than the RoV (max) value. The total amount of reactives comprises all the vitrinite, liptinite and reactive semifusinite present in the sample, resulting in a large proportion (84.0%). The total amount of inerts (16.0%), which is somewhat lower than the calculated amount of 21.4% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.75, which is somewhat smaller than 1, indicating a coal with an excess in reactive macerals. High coking potential is predicted in terms of the drum indices which is supported by the excellent free swelling and Roga indices (8.5 and 85 respectively).

The rheological properties in Table 8 Appendix 1 exhibit good maximum dilatation and excellent maximum fluidity, which will be beneficial for the coke quality. The ash composition exhibits very low phosphorus content, with a somewhat high alkali content due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.24 Wells Coke

The results shown in Table 12 Appendix 1 indicate a coke with a high binder phase (80%) and filler phase (20%). This is indicative of a high vitrinite coal, with a high percentage of reactives. Figure 4 Appendix 2 shows an example of the filler phase.

The results in Table 15 Appendix 1 indicates a small amount of the binder phase being isotropic (2%) but the incipient anisotropic is high (13%) and will have an effect of the coke properties, with 85% in the anisotropic carbon form. The 85% of the anisotropic carbon is located in the circular form which is indicative of a lower ranking coal. An example of the circular carbon form is shown in Figure 3 Appendix 2. The circular form may affect the mechanical strength of the coke and the reactivity of the coke. Indicated in Table 18 Appendix 1 the CRI is low (23.5) and the CSR moderately high (56.8).

The coke has a reasonable $M40/_{30}$ index of 62.4 and a low $M10/_{30}$ index of 8.6. This is expected for the rank of coal. These tolerable values are probably due to the high fluidity and dilatation of the parent coal.

Figure 11 Appendix 1 shows the reflectance distribution of the coke, which ranges between 5.6 and 11.2 resulting in a mean reflectance of 7.31 indicating that the coal, was well graphitised in the process.

1.1.25 Cedar Grove Coking Coal

The results in Table 7 Appendix 1 indicate a coal with low ash and to some extent high sulphur contents, high free swelling index and high Roga index (8.5 and 87 respectively). The maceral composition of the sample exhibits moderately high vitrinite content (74.4%), a fairly high amount of liptinite and subordinate amounts of reactive semifusinite, inert semifusinite and traces of fusinite, secretinite and micrinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The moderately high volatile matter content is indicative of a medium rank coal. The vitrinite reflectance distribution rages from V-class 7 to 12, resulting in a mean maximum reflectance of vitrinite, RoV_{max}, of 1.04%. Although all the reactive semifusinite in the sample is regarded as reactive, the amount is somewhat diminutive to have any significant effect on the reflectance parameter RoR, which is indicative of the rank of the total amount of reactives in the coal. It is therefore almost similar to the RoV_{max} value. The total amount of reactives comprises all the vitrinite, liptinite and reactive semifusinite present in the sample, which amounts to 84.0%. The total amount of inerts is 16.0%, which is somewhat lower than the calculated amount of 22.0% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.73, which is smaller than 1. This is indicative of a coal with a high proportion of reactive macerals. Remarkable coking potential is predicted in terms of the drum indices, which is supported by the excellent free swelling and Roga indices, is predicted.

The rheological properties in Table 8 Appendix 1 exhibit excellent values for maximum dilatation and maximum fluidity, which will be beneficial for the coke quality. The ash composition exhibits very low phosphorus content, whereas the alkali content is high due to the high potassium content. The ash fusion temperatures are favourably high.

1.1.26 Cedar Grove Coke

The results in Table 12 Appendix 1 indicates a coke with a high binder phase (82%) and a filler phase (18%) indicative of a medium vitrinite coal, with a high percentage of reactives, although the coal does not have such a high vitrinite content there is liptinite and reactive semifusinite present. The vitrinite reflectance spread is over a wide range of V-classes which may indicate multiple seam mining.

The results in Table 15 Appendix 1 indicate a low amount of the binder phase being isotropic (1%) and incipient anisotropic (2%) with 97% as anisotropic carbon forms. All of the anisotropic carbon is located in the circular form which is indicative of a lower ranking coal. The circular form can affect the mechanical strength of the coke and the reactivity of the coke. However this circular carbon form falls in the medium range moving closer to the lenticular form hence the reason for the above expected reactivities and mechanical strengths. Shown in Table 18 Appendix 1 the CRI is low (24) and the CSR moderately high (60.1).

The coke has a reasonable $M40/_{30}$ index of 63.6 and a low $M10/_{30}$ index of 8.1, which can be expected for this rank of coal.

Figure 12 Appendix 1 shows the reflectance distribution of the coke, which ranges between 5.2 and 10.8 resulting in a mean reflectance of 7.34 indicating that the coal was well graphitised in the process, but that the rank of the parent coal was low and the degree of order could not be reached.

1.6 Australian Coals and Cokes

1.2.1 Riverside / Goonyella (RGB) Coking Coal

The results in Table 9 Appendix 1 indicate a coal with low ash and low sulphur contents, high free swelling index and high Roga index (9 and 80 respectively). The maceral composition of the sample exhibits a moderately low vitrinite content (59.5%) which is indicative of a Gondwanaland coal, with no amount of liptinite detected and high amounts of reactive semifusinite and inert semifusinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

Due to the moderately low vitrinite content and the reasonable reactive semifusinite the volatile content is not a good indicator of rank, we can see that there is significant difference in the RoV_{max} and the RoR this is mainly due to the amount of reactive semifusinite. If we were to look at a coal like Twin Rock (4.1.1 above) we can see that it contains only vitrinite and no reactive semifusinite which results in the RoV_{max} and RoR being the same. This is the major indicator for distinguishing a Northern and Southern hemisphere coal. The volatile matter content is indicative of a medium rank coal although this is not a true indicator for rank on Southern hemisphere coals. The vitrinite reflectance distribution ranges from V-class 10 to 13, resulting in a mean maximum reflectance of vitrinite, RoV_{max}, of 1.19%. The total amount of reactives comprises all the vitrinite and reactive semifusinite present in the sample, which results in a medium amount (75.1%). The total amount of inerts is 24.9%, which is higher than the calculated amount of 19.9% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample.

The ratio of total inerts/optimum inerts results in a composition balance index of 1.32, which is larger than 1. This is indicative of a coal with a high proportion of inert macerals. Good coking potential is predicted in terms of the drum indices, which is supported by the excellent free swelling and Roga indices.

The rheological properties in Table 10 Appendix 1 exhibit excellent values for maximum dilatation and reasonably maximum fluidity. The maximum fluidity could be attributed to the amount of inerts but is not necessarily always the case, according to some literature any value between 200 and 1000 ddpm's should work well. The ash composition exhibits very low phosphorus content. The ash fusion temperatures are favourably high.

1.2.2 Riverside / Goonyella (RGB) Coke

The results shown in Table 13 Appendix 1 indicates a coke with an extremely low binder phase (61%) and a filler phase (39%) indicative of a low vitrinite coal, with a low percentage of reactives, although the coal has a low vitrinite content there is reactive semifusinite present (12.1%) making a classic example of a Gondwana coal, where the results will differ to that expected.

The results in Table 16 Appendix 1 indicates a low amount of the binder phase being isotropic (2%) and no incipient anisotropic with 98% as anisotropic carbon forms. Most of the anisotropic carbon is located in the circular form and 23% in the lenticular form which is indicative of a lower ranking coal although the rank is 1.2 RoV_{max}. The circular form can affect the mechanical strength of the coke and the reactivity of the coke. However this circular carbon form falls in the medium range moving closer to the lenticular form hence the reason for the above average mechanical strengths. Shown in Table 19 Appendix 1, the CRI is (25.8) and the CSR moderately high (61.9) still within limits but indicative of the low percentage binder phase.

The coke has a high $M40/_{30}$ index of 78 and a low $M10/_{30}$ index of 8.3, which is expected for this rank of coal.

Figure 14 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.2 and 11.6 resulting in a mean reflectance of 7.93 indicating that the coal was well graphitised in the process.

1.2.3 Oaky North Coking Coal

The results in Table 9 Appendix 1 indicate a coal with reasonable ash and low sulphur contents, high free swelling index and high Roga index (9 and 84 respectively). The maceral composition of the sample exhibits a reasonable vitrinite content (78.7%) which is relatively high for a Gondwana coal, with no amount of liptinite detected and low amounts of reactive semifusinite, inertinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

Due to the high vitrinite content and the low reactive semifusinite the volatile content in this Gondwana coal presents itself more towards a northern hemisphere coal than a Southern one putting it in the “mid vol” class. The vitrinite reflectance distribution ranges from V-class 11 to 14, resulting in a mean maximum reflectance of vitrinite, RoV (max), of 1.29%. The total amount of reactives comprises all the vitrinite and reactive semifusinite present in the sample, which results in an amount of 80.7%. The total amount of inerts is

18.7%, which is lower than the calculated amount of 21.3% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample. This indicates a coal that would contribute to total reactive component of the blend, resulting in more mesophases being formed and hence combining or reacting with other coals to from more anisotropic coke.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.96, which is almost than 1. This is indicative of a well balanced coal which in most likelihood could produce a good quality coke for the blast furnace by itself. Good coking potential is predicted in terms of the drum indices, which is supported by the excellent free swelling and Roga indices.

The rheological properties in Table 10 Appendix 1 exhibit excellent values for maximum dilatation with a coking window of 90 ^{o}C, the larger this window is it will seemingly influence the degree of graphitisation resulting in a coke having higher anisotropic component. The ash composition exhibits very high phosphorus content. The ash fusion temperatures are favourably high.

1.2.4 Oaky North Coke

The results shown in Table 13 Appendix 1 indicates a coke with a high binder phase (82%) and a filler phase (18%) indicative of a medium vitrinite coal, with a high percentage of reactives. Figure 6 Appendix 2 is a good example of the bonding between filler and binder phases in coke.

The results in Table 16 Appendix 1 show a low amount of isotropic binder phase (2%) and no incipient anisotropic with 98% anisotropic carbon forms. Almost all of the anisotropic carbon is located in the lenticular form which is indicative of a medium ranking coal. An example of the lenticular carbon form is shown in Figure 5 Appendix 2. The lenticular form is supported by the excellent reactivities and mechanical strengths. Table 19 Appendix 2 shows the CRI is extremely low (16.1) and the CSR extremely high (72.2), this coal will have a definite major contribution to a coking coal blend.

The coke has a high $M40/_{30}$ index of 78 and a low $M10/_{30}$ index of 8.3, which is in expectation for the rank of coal.

Figure 15 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.2 and 14.6 resulting in a mean reflectance of 8.71 indicating that the coal was well graphitised in the process, and that the degree of order is extremely high-the highest of all the coal tested. These results are also supported by the high dilatation results and the high fluidity, the high resolidification temperature is probably the reason for the high mean reflectance of the coke.

1.7 South African Coals and Cokes

1.7.1 Grootegeluk Coal

The results in Table 9 Appendix 1 indicate a coal with low ash and high sulphur content, high free swelling index and high Roga index (6 and 78 respectively). The maceral composition of the sample exhibits a high vitrinite content (88.5%), with a small amount of liptinite and subordinate amounts of reactive semifusinite and inert semifusinite. The relatively small amount of mineral matter is a reflection of the low ash content of the sample.

The extremely high volatile matter content (38.1 db) is indicative of a high rank coal, where the vitrinite reflectance distribution ranges between V-class 0.6 to 0.8, resulting in a mean maximum reflectance of vitrinite, RoV_{max} of 0.74%. Although all the reactive semifusinite in the sample is regarded as reactive, the amount is somewhat small to have any significant effect on the reflectance parameter (RoR), which is indicative of the rank of the total amount of reactives in the coal. It is therefore only slightly higher than the RoV_{max} value. The total amount of reactives comprises all the vitrinite, liptinite and reactive semifusinite present in the sample, which results in a large amount of 91.1%. The total amount of inerts is 8.9%, which is much lower than the calculated amount of 17.5% optimum inerts in the coal.

The ratio of total inerts/optimum inerts results in a composition balance index of 0.51, which is much smaller than 1, indicating a coal with an excess in reactive macerals. Very good coking potential, which is supported by the excellent free swelling and Roga indices, is predicted based only on the swelling and Roga index. However the rank of the coal is so low that it is exceptional to have these results for swelling and Roga, but could be attributed to the high amount of reactives.

The rheological properties in Table 10 Appendix 1 exhibit extremely low maximum dilatation and almost no maximum fluidity, which will be detrimental for coke quality. The ash composition exhibits very low phosphorus content. The ash fusion temperatures are favourably high.

1.7.2 Grootegeluk Coke

The results shown in Table 13 Appendix 1 indicates a coke with an extremely high binder phase (82%) and a filler phase (17%) indicative of a high vitrinite coal, with a high percentage of reactives.

The results in Table 16 Appendix 1 indicates an excessively high amount of the isotropic binder phase (97%) and incipient anisotropic (1%) with anisotropic carbon forms only (2%). Figure 7 Appendix 2 illustrates the isotropic carbon form in the binder phase. The anisotropic carbon is located in the circular form (shown in Figure 8 Appendix 2). The above mentioned results are indicative of an extremely low ranking coal. The high percentage of isotropic carbon forms in the binder phase will have detrimental effects on the cokes properties and would most likely have the same effect on the overall blend if used in a coking coal blend. Isotropic forms of carbon are normally associated with high ranking coals which has low or no fluidity and tend to have poor dilatations, which is the case with this coal. Here one can see the effect predominately on the reactivities of the coke which supports the statement that isotropic coke forms react much more readily with carbon dioxide which has a much higher CRI result as is shown in Table 19 Appendix 1. The coke from this coal produced high CRI (44.2) and as the CRI levels increase so does the CSR decrease as to give a result of 31.7. Isotropic carbon forms will affect the mechanical strength as well which is shown in Table 19 Appendix 1 with a $M40/_{30}$ of 28 and $M10/_{30}$ 9.7, the stability factor also shows the effect of the large isotropic carbon percent.

Figure 16 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 5.2 and 9.5 resulting in a mean reflectance of 7.09. Indicating that carbonisation was achieved but with the coal not exhibiting any great rheological results dreadfully little amounts of mesophases formed resulting in little carbon ordering tanking place this is evident in Figure 7 Appendix 2.

1.7.3 Tshikondeni Coking Coal

The results in Table 9 Appendix 1 indicate a coal with high ash and reasonable sulphur contents, high free swelling index and high Roga index (9 and 87 respectively). The maceral composition of the sample exhibits a high vitrinite content (81.1%) which is relatively high for a Gondwana coal, with no liptinite detected and low amounts of reactive semifusinite and a high amount of inerts. The high amount of mineral matter is a reflection of the high ash content of the sample.

The volatile content is low which indicates a high ranking coal. The vitrinite reflectance distribution ranges between V-class 12 to 16, resulting in a RoV_{max} of 1.49%. The total amount of reactives comprises all the vitrinite and reactive semifusinite present in the sample, which results in an amount of 81.1%. The total amount of inerts is 18.9%, which is much higher than the calculated amount of 8.2% optimum inerts in the coal, the latter being indicative of the amount of inerts required for the strongest coke possible for the specific rank of the sample. Indicating a coal with high amounts of un-reactives (inert vitrinite) in the V-classes, this however could be the result of heat affected coal due to geological effects.

The ratio of total inerts/optimum inerts results in a composition balance index of 2.3, which is much higher than 1. This is indicative of a reactive poor coal. Good coking potential is predicted, which is supported by the excellent free swelling and Roga indices.

The rheological properties in Table 10 Appendix 1 exhibit excellent values for maximum dilatation (113%) and good maximum fluidity (1356 ddpm) with a coking window of 82 ^{o}C. The ash composition exhibits very high phosphorus content. The ash fusion temperatures are favourably high.

4.3.4 Tshikondeni Coke

The results shown in Table 13 Appendix 1 indicate a coke with a moderate binder phase (76%) and a filler phase (22%) indicative of a medium vitrinite coal, with a high percentage of reactives.

The results in Table 16 Appendix 1 indicate no isotropic binder phase and no incipient anisotropic carbon forms with 100% anisotropic carbon forms in the binder phase. Almost all of the anisotropic carbon is located in the lenticular form which is indicative of a medium ranking coal although the coal has a rank of 1.49. Figure 9 Appendix 2 show the lenticular carbon form clearly. The lenticular form is supported by the high reactivities and mechanical strengths. Shown in Table 19 Appendix 1 the CRI is low (20.8) and the CSR extremely high (66.2), this coal will have a definite major contribution to a coking coal blend.

The coke has a high $M40/_{30}$ index of 74.9 and a low $M10/_{30}$ index of 7.4, which is expectation for the rank of coal.

Figure 17 Appendix 1 shows the reflectance distribution of the coke, which has a distribution between 1.7 and 14.7 resulting in a mean reflectance of 7.81 indicating that the coal was well graphitised in the process, and that the degree of order is high. These results are also supported by the high dilatation results and the high fluidity, the high resolidification temperature is probably he reason for the high mean reflectance of the coke.

DISCUSSION

5.1 Correlations and Observations

Results presented in the previous chapter are now discussed and correlated and statements made regarding which parameters in the coal have a major influence on the coke quality. The statements made with respect to this research and the approach followed should be viewed as single coal to single coke and not as a single coal's behaviour in a blend of coals to produce a coke. Most of the arguments will probably hold true when the coals are mixed in a blend of coking coal to produce coke. The variation in the reactions between coals when mixed in a blend will be left for future work, due to the levels of complexity involved.

Firstly the coals can be grouped in three major groups with respect to their rank i.e. as determined by the vitrinite reflection (%RoV_{max}), as this is the first important common denominator in coals for the assessment of their qualities.

Namely:

1. Group 1 (rank<1)
2. Group 2 (rank 1 to 1.5)
3. Group 3 (rank >1.4)

Group 1 includes the following coals:

• Grootegeluk	(coal No. 16)
• Arch Export	(coal No. 3)
• Knox Creek	(coal No. 2)
• Cedar Grove	(coal No. 12)

Group 2 includes the following coals:

• Marfork Eagle	(coal No.13)
• Wells	(coal No. 11)
• Blue Creek No. 4	(coal No. 8)
• RGB	(coal No. 14)
• Shoal Creek	(coal No. 4)
• Oaky North	(coal No. 15)
• Twin Rock	(coal No. 1)
• Oak Grove	(coal No. 7)
• Blue Creek No. 7	(coal No. 9)
• Tshikondene	(coal No. 17)

Group 3 includes the following coals:

• Alpha Aimfire	(coal No. 5)
• Alpha Kepler	(coal No. 6)
• Pinnacle	(coal No. 10)

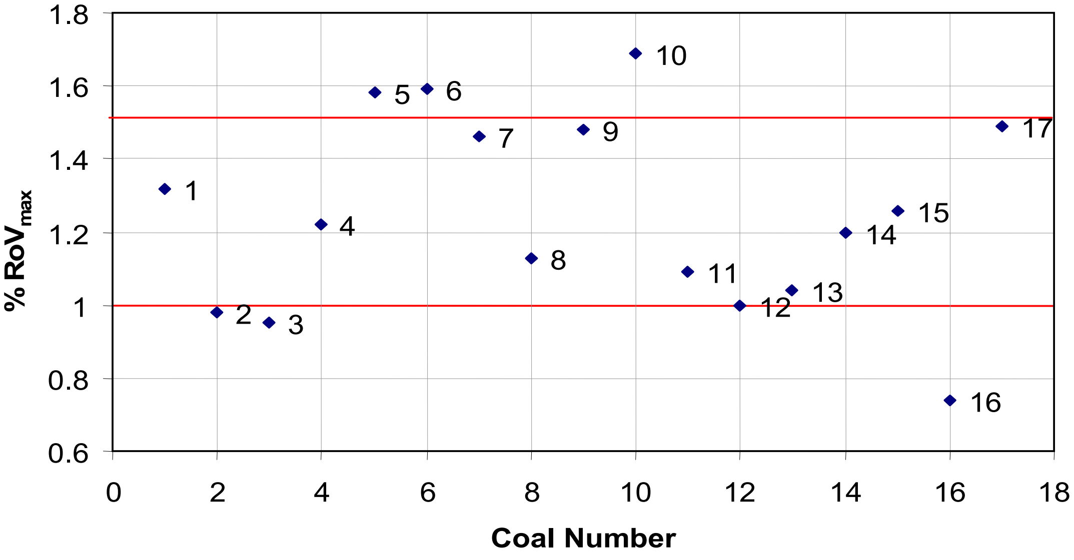


Figure 0.1 Distribution of coals based on their rank

The groups are shown in Figure 5.1. The red lines indicate the boundaries between the groups.

One of the best correlations with the rank of coal was found to be the Resolidification Temperature of the coal in the Gieseler plastometer. This is shown in Figure 5.2. There are numerous theories about fluidity and the degree thereof, but to date this is still classified to be a phenomenon of an individual coal. However as illustrated in Figure 5.2 it would appear that fluidity and the resolidification temperatures of a coal are closely related to the rank of a coal as expressed by vitrinite reflectance i.e. the higher the rank the higher the resolidification temperature of the coal.

These factors are strongly correlated with the quality of the coke. From the coals and cokes tested the majority adhere to the following statements;

I. the higher the rank the higher the resolidification temperature
II. the higher the resolidification temperature the higher the anisotropic carbon forms in the coke
III. the higher the anisotropic carbon forms the higher the M40/$_{30}$ index
IV. the higher the M40/$_{30}$ index the higher the CSR and lower the CRI reactivities.

These statements are however very broad and, as can be seen in the following figures, the majority of the coals follow these statements but there are those that do not. Statement (I) is shown in Figure 5.2 below. Here it is evident that the lower rank coals produce lower resolidification, however it also evident that as a coal increase to a rank of 1.5 (%RoV$_{max}$) there is a slight drop off in the resolidification process. This is most probably best explained by the loss of volatile matter and to greater reordering of the carbon molecules in the reactives rendering them more inert i.e. less fluid in the coking process. This trend appears to continue as the rank increases.

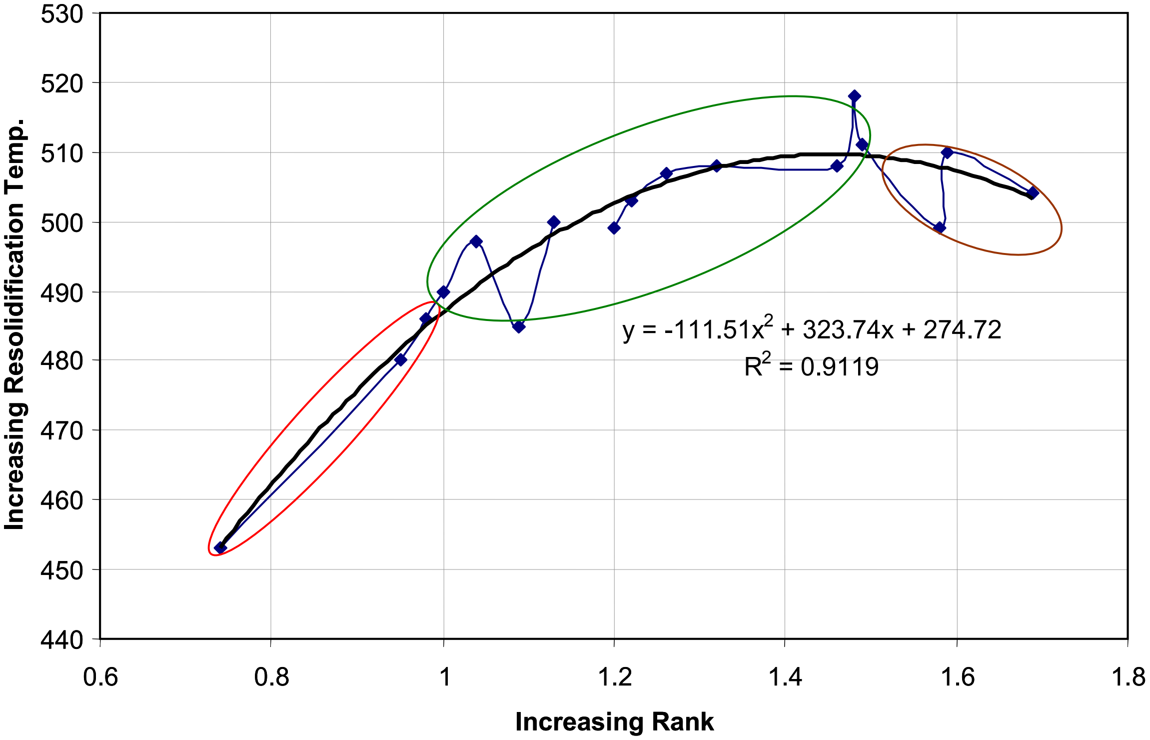


Figure 0.2 Relation of rank to resolidification temperature

If one considers the trend in Figure 5.2 to be representative of most coals then it may be possible to calculate the resolidification temperature for a coal by knowing the rank of that coal. It must however be stated that this equation may only hold true for the coals in this experiment and may not apply to all coals.

A polynomial trendline is a curved line that is used when data fluctuates. It is useful, for example, for analyzing gains and losses over a large data set. The order of the polynomial can be determined by the number of fluctuations in the data or by how many bends (hills and valleys) appear in the curve. The equation has an r^2 of 0.9119 the r^2 value being a number from 0 to 1 that reveals how closely the estimated values for the trendline correspond to the actual data. A trendline is most reliable when its r^2 value is at or near 1 this is also known as the “coefficient of determination”.

$$Rt = -111.51 \times RoV \max{}^2 + 323.74 \times RoV \max + 274.72$$

Where Rt is the resolidification temperature and RoV_{max} the rank of the coal.
It is also evident (Figure 5.3) that with an increase in the resolidification temperature of a coal the more likely the coke would comprise of a higher amount of anisotropic carbon

forms in the coke's binder phase. In literature Loison R et al.(2002) it is well documented that anisotropic coke is less prone to be consumed by carbon dioxide, then if the amount of anisotropic carbon forms increase in the coke then its reactivity should decrease and its strength after reaction should increase. From the coals and cokes results it can be said that statement (II) is correct as shown in Figure 5.3.

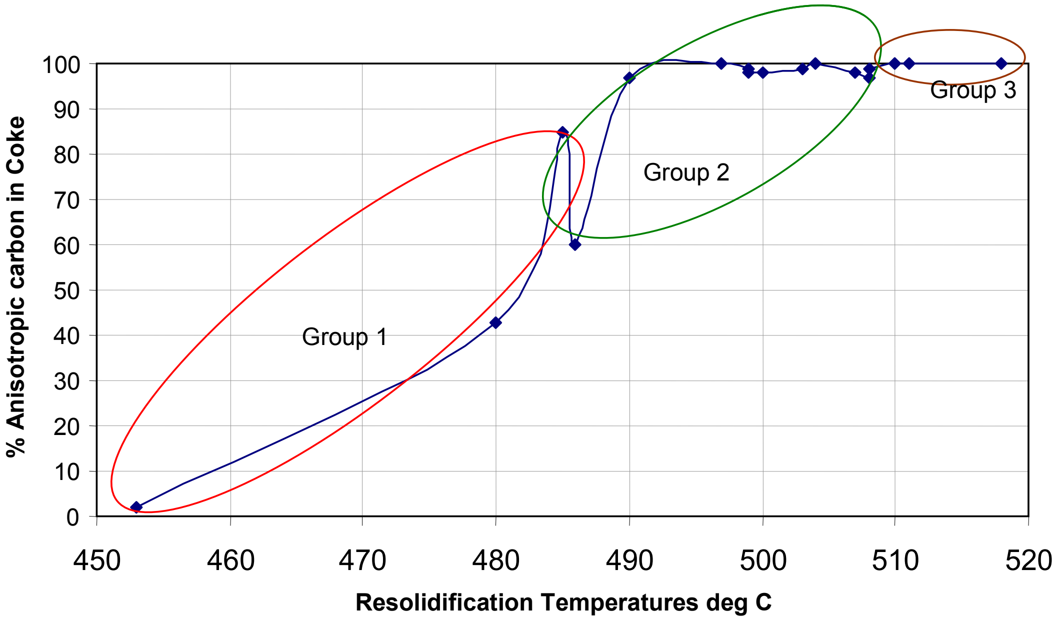


Figure 0.3 Increasing Resolidification Temperature resulting in increasing % anisotropic carbon in binder phase

As the amount of anisotropic carbon forms in the coke increases so the cold strength of the coke increases which is evident form the results on the M40/$_{30}$ index as shown in Figure 5.4. However we can see that as the graph reaches 95% anisotropic carbon in the binder phase of the coke, fluctuations in the M40/$_{30}$ index occurs. This is likely to be due to the different forms of anisotropic carbon forms that occur at this stage i.e. circular, lenticular and ribbon types. If most of the anisotropic carbon is in the lenticular form, then the M40/$_{30}$ seems to increase but as the form shifts to the ribbon type the M40/$_{30}$ index starts to decrease. This could also be due to the drop off in coking capacity of the high ranking coals.

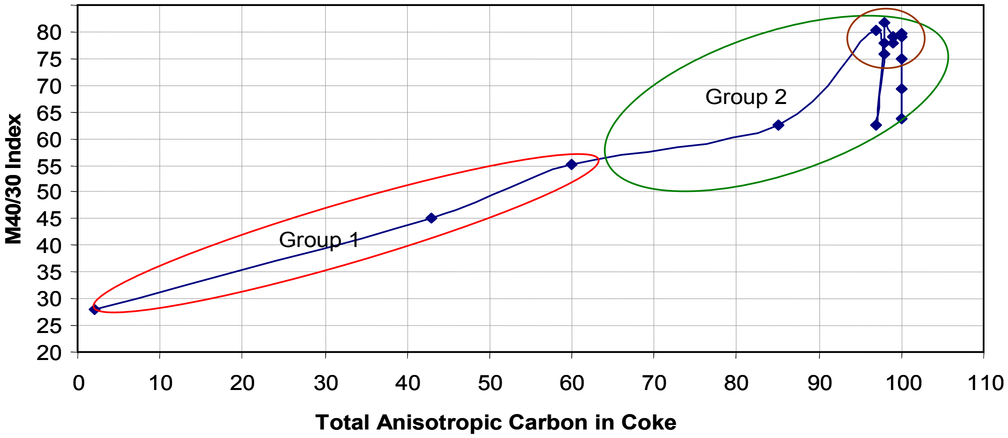


Figure 0.4 Increasing M40/30 Index due to Increasing % Anisotropic Carbon in binder phase

The results may also infer that some of the carbon forms classified as anisotropic, especially the ribbon type, may have an isotropic molecular structure. This will become much more evident in the reactivities. Further research work in this regard should be done in future.

In Figure 5.5 we can see that rank which is reflected in the percentage anisotropic carbon in the binder phase follows the rule that higher rank provides more anisotropic coke and is less reactive towards carbon dioxide up to the third group, which is the highest ranking group. The latter group has high amounts of anisotropic carbon forms in the binder phase of the coke (between 99 and 100%) and most of their anisotropic carbon forms are in the ribbon flow form. This group tends to be almost as reactive to carbon dioxide as the low ranking coals in group 1 which have the high isotropic carbon forms in the binder phase.

This phenomenon can not be explained as yet but could be speculated on. The coals which have a high rank (still within coking range) produce high amounts of anisotropic carbon forms in the binder phase, but all have poor rheological results i.e. dilatation and fluidity. This could result in production of anisotropic carbon forms due to rank, but this carbon form is anisotropic on a macro scale (as seen by petrography of the coke), but on the micro scale it might not have ordered and is still isotropic. This could explain the CRI and CSR results, but these coals produce coke with high M40/$_{30}$ indices which is normally associated with low CRI and high CSR cokes.

It would appear that coke on the macro scale exhibits anisotropic carbon forms and behaviour but on the molecular scale it reacts like isotropic carbon which has reversed properties and would be unsuitable for the blast furnace. This is not the best coke with regard to its high reactivity to feed into a blast furnace as coke of this quality would deteriorate as it weakens in strength under load of the furnace feed (Loison R et al. 2002). The coal could however, be an additive in processes like submerged arc furnaces where cold strength is desired in order to minimise fines being generated in the feed handling, but requires the coke to be reactive so as not to end up in the final product when being tapped.

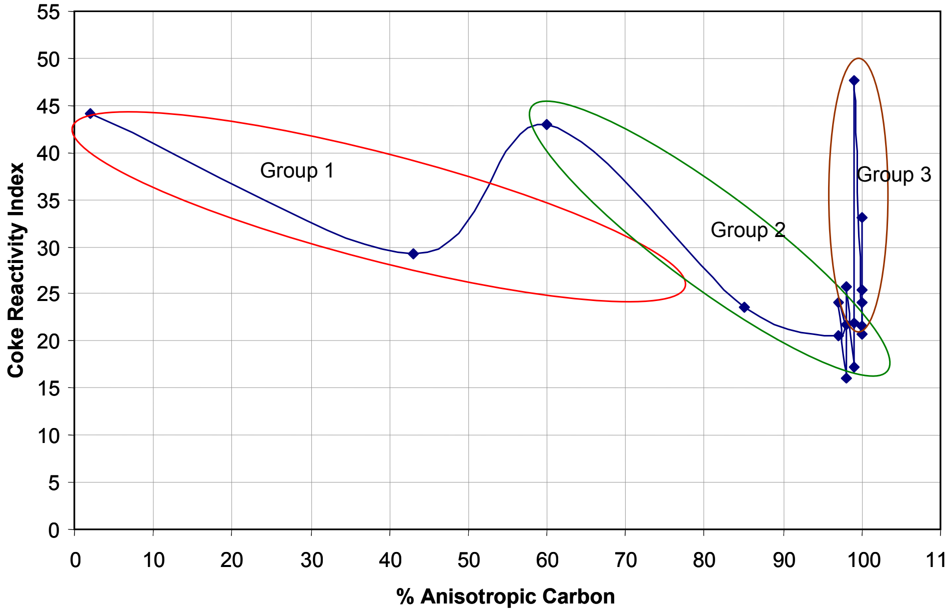


Figure 0.5 Decreasing CRI with Increasing % Anisotropic carbon forms

As can be seen in Figure 5.6 below there is a well established link between CRI and CSR. As CRI increases, CSR decreases. The r^2 indicates a significantly high degree of correlation (0.93).

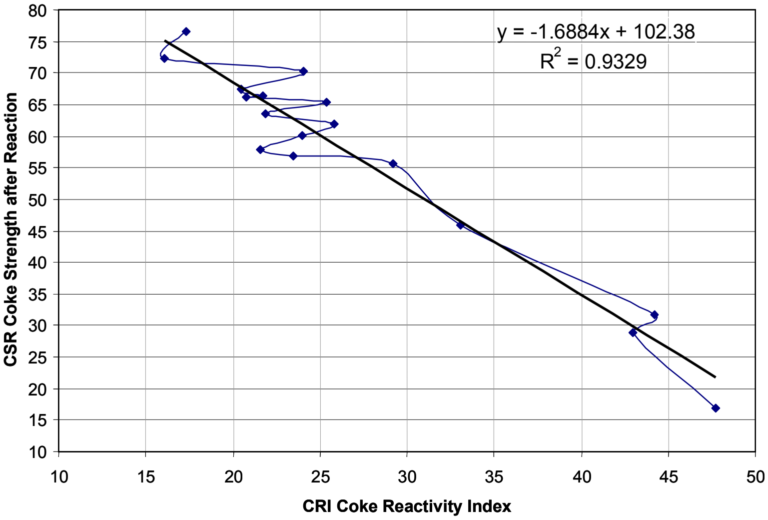


Figure 0.6 The relation of CSR to CRI

The good correlation between the CRI and CSR is predominately due to the samples being subjected to two parts of the same analytical test, however the scatter of the data in the centre suggests that there might be an error in the fundamentals of the test or that other factors are affecting the coke i.e. ratio of different anisotropic carbon forms, like the way that the ribbon type anisotropic carbon form can behave as an isotropic carbon form.

Thus far this report has established that the three essential coke quality parameters are influenced by a number of coal quality parameters but if one was to evaluate these parameters directly with the rank of the coal one finds that the correlation starts to disappear as shown in Figure 5.7. This however is not to say that the rank of the coal related to the qualities in the coke but that a combination of petrographic and rheological properties of the coal are responsible for the coke quality. This is indicated by the poor correlation as the r^2 is only 0.39.

It is essential when evaluating coal for use in a coking coal blend to understand both the petrographic results as well as the rheological results, in order to obtain a more representative assessment.

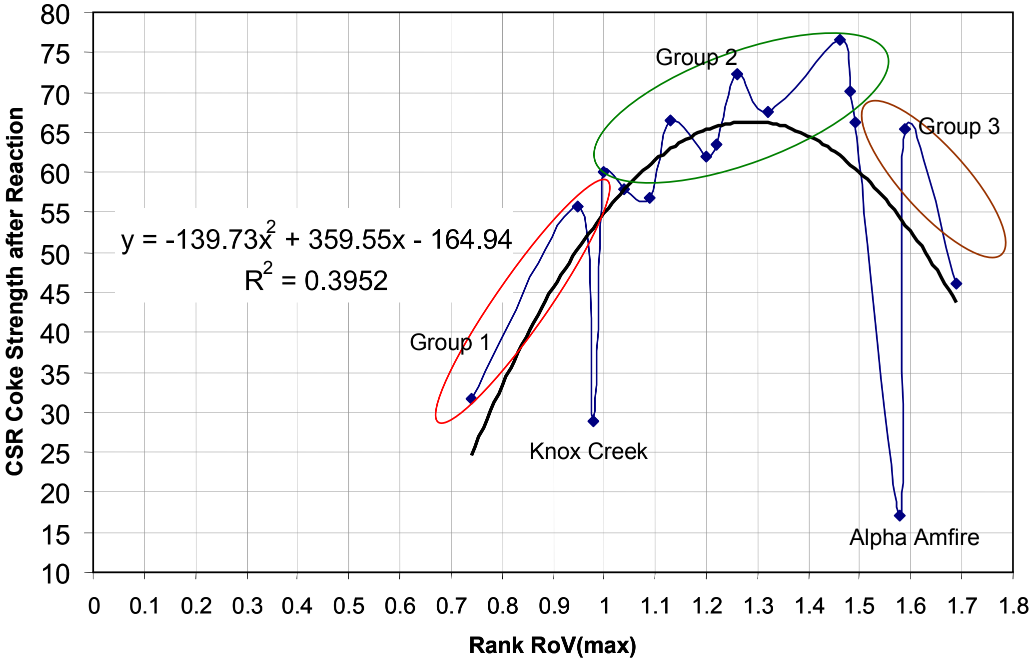


Figure 0.7 Relation between coal rank and Coke strength after reaction

In order to establish whether or not this combined argument is possible an attempt has been made to produce a characterisation formula or system to best describe the coal qualities in relation to their coke qualities. This however is only likely to be applicable for single coal components. Further studies are necessary to look at the way blends perform with respect to their coal components.

With regard to performance in a coke plant a specific constant referred to as the G-Factor is used in calculating the $M40/_{30}$ index. The G-Factor was developed by the Germans in the late 1970's. This factor basically combines all the dilatation results into one result with out any units. This factor is then used to predict M40 index on a specific coke plant. It must be noted that this factor was engineered for large slot ovens and needed to be used with the coking rate of that specific battery of coking ovens. However for the current tests the oven and the coking rates were kept constant so we will use the G-Factor was elected for use in this research programme. The equation is as follows:

$$G\_Factor = \frac{DT1 + DT2}{2} \times \frac{Contraction + MaxDil}{(DT3 \times Contraction) + (DT1 \times MaxDil)}$$

Where:
DT1 is the temperature of softening
DT2 is the temperature of max contraction
DT3 is the temperature of max dilatation
Contraction is the % max contraction
MaxDil is the % max dilatation

In practice the G-factor is used in conjunction with plant specific parameters to predict the possible M40 Index value or the fluctuation of the M40 index if plant parameters were to be changed. For the purpose of this research the G-Factor is only used to combine and correlate the dilatation properties of the coal to its resulting coke properties.

A principle similar to the G-Factor was developed by the writer for the Fluidity Factor. This proposal seeks to combine all the Gieseler Fluidity results into one result to determine whether it can assist in the assessment of coal to predict coking quality.

The Fluidity Factor is as follows:

$$F\_Factor = \frac{FT1 + FT3}{2} \times \frac{MaxFluidity + Coke.W}{MaxFluidity \times FT2}$$

Where:
FT1 is the initial softening temperature
FT2 is the temperature of maximum fluidity
FT3 is the temperature of resolidification
MaxFluidity is the dial divisions per min. ddpm's
CokeW is the coking window which is the FT3 – FT1 which gives the time the coal would be in a fluid sate during coking when combined with the coking rate of an oven.

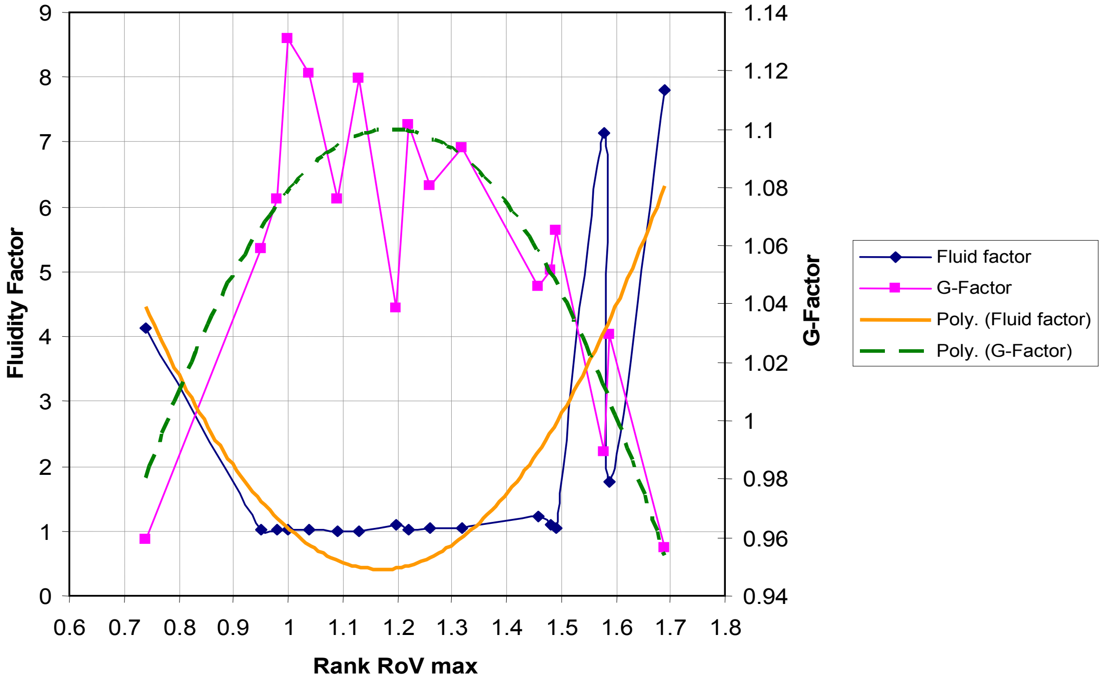


Figure 0.8 Relation between G-Factor and Fluidity Factor based on Rank

From the fluidity and dilatation data Figure 5.8 was derived. Here it will be noted that there is a relationship between the G-factor, Fluidity-Factor and Rank, i.e. examination of the rheological results, indicates that it is not just one of the dilatation or fluidity results that equate with the rank of the coal but all of the factors combined.

From Figure 5.8 one could now deduce that the best coals to select would most probably be in a rank range of 1.1 to 1.4 with a Fluidity factor close to 1 and a G-Factor in the range of 1.06 to 1.1. So if a coal was to have the suitable rank and produces the relevant rheological results for dilatation and fluidity it should produce an acceptable coke with acceptable anisotropic carbon in the binder phase of the coke.

5.2 Descriptions of the main coal groups

It is clear that from all the above that each of the three major groups of coals produce their own characteristics. The groups were divided on the bases of their individual rank i.e. low rank (RoV max 0.6 to 1) middle rank (RoV max 1 to 1.5) and high rank (RoV max 1.5 and higher). Although it was established that the coke quality could not always be directly linked to their respective ranks, when linked with petrographic and rheological properties associated within each rank, the relationship to coke quality was evident.

Group 1

The low ranking coal, produced predominately isotropic carbon forms in the binder phase. This was mainly due to the low ranking vitrinite content and its poor dilatation and fluidity characteristics, which resulted in high reactivity (CRI) and low hot strength (CSR). Such coals may have a low $M40/_{30}$ index if the vitrinite content is high, but if the composition balance is close to 1 then it is possible to have a moderate $M40/_{30}$ index. Low ranking coals that contain reasonable amounts of reactive semifusinite will tend to produce higher cold strengths due to the mechanical strengths added by semifusinite. A lower $M40/_{30}$ index will result in a higher $M10/_{30}$ index which means that the coke product will produce larger amounts of fine material which cannot be used in the furnaces.

In summary group 1 type coals should only be added to a coke blend for cost benefits and only if the rest of the coals in the coking coal blend could accommodated the overall deterioration of the coke quality in the blend. However coals from group 1 could be used in producing coke for processes where the cold strength is not a limiting parameter and where higher reactivities are needed. They may also be used in processes where higher resistivity is needed for converting electrical current to heat, isotropic carbon forms tend to have higher resistivities than anisotropic carbon forms. It is also possible to increase the $M40/_{30}$ index by utilising different coking technologies like the non-recovery coke ovens, but is unlikely to produce better hot strengths.

Group 2

The middle ranking coals could be described as the prime coking coal group. The coals in this category produce petrographic and rheological results which could be used fairly accurately in predicting the quality of coke produced from these coals. Coals in this group tend to have higher dilatations and fluidity values, and larger coking “windows” which result in producing higher anisotropic carbon forms in the binder phases. Anisotropic carbon forms resulted in lower reactivity to carbon dioxide (CRI) which in turn resulted in higher hot strengths. This is an advantage when used in a process where the coke is required to maintain integrity under high load and temperature conditions. This can also be a disadvantage if the coke is used in processes where higher reactivities are required in order to limit the amount of unreacted carbon in the product of the process.

In general this group is suitable to produce coke for a blast furnace type operation. The higher anisotropic carbon forms tend to have an effect on the cold strength by producing higher $M40/_{30}$ and lower $M10/_{30}$ index results. However the better rheological results encountered in the tests were probably produced through development of a different pore structure (which was not tested in this exercise). This is likely to result in thicker cell walls which in turn would result in higher cold strengths.

Group 3

Group 3, the high ranking coals, lie on the border line of "cokable" coals and they proved to have abnormal behaviour. This was evident from the petrographic and rheological results. In the petrographic results there are high ranking V-classes and these high ranking classes tended to react in the same manner as inertinite macerals, namely by low proportions of devolitisation and by not showing any change in structure. Such coals merely become solid unreacted parts of the filler phase in the coke. This group of coals also exhibited poor dilatation and fluidity. However the most interesting result was that they still produced high amounts of anisotropic carbon forms in their binder phase should have imparted to these cokes low reactivities and high hot strengths, but this was not the case. Coals with poor fluidity normally have a poor coking window which results in carbon forms with poor order hence high amounts of isotropic carbon forms in the binder phase. The coals under review have poor fluidity results but high amounts of anisotropic carbon forms. The reactivity and hot strengths showed that these anisotropic carbon forms behaved as if they were isotropic by producing high reactivity to carbon dioxide. This gives the impression that although they are classified as anisotropic carbon in the petrographic analysis, they are in fact not. These anomalous observations could be a result of the high ranking V-classes in vitrinite which could have already been in the macro anisotropic range, but on the molecular level they are still isotropic. In conjunction with the poor rheological properties, these structures or carbon forms are carried over to the coke. These specific macro anisotropic carbon forms tend to return reasonable high cold strengths which were evident in the $M40/_{30}$ index results.

These coals will have a deteriorating effect on the overall coke quality if used in a blend. These cokes would also not be adequate for the blast furnace operation, but could rather be used in processes where high cold strength is required to reduce fines generation in the material handling process. However high reactivities are also needed, which is normally not associated with high cold strengths.

5.3 Equations derived from data

These equations were derived from the data to illustrate the different coal parameters influencing coke qualities when produced from coals in different groups.

Group 1

M40/30 Index = *-1.954* x *% Volatile Matter (ad) + 0.664* x *Coking Window + 2.46* x *Fluid Factor + 66.278*

CSR = *-2518.12* x *% RoV (max) + 6.87* x *Coking Window -108.8* x *Fluid Factor + 2084.4*

Group 2

M40/30 index = *-2.54* x *% Volatile Matter (ad) -43.11* x *% RoV (max) -24.3* x *Fluid Factor + 220.64*

CSR = *-0.409* x *%Volatile Matter (ad) + 9.07* x *% RoV (max) + 27.8* x *Fluid Factor + 35.4*

Group 3

M40/30 index = *0.6105* x *Coking Window + 0.908* x *Fluid Factor + 45.86*

CSR = *-2.18* x *Coking Window + 12.588* x *Fluid Factor + 202.89*

The above equations may only likely to be valid for the coals under review at present but the principle proposed is to obtain correlations in each group classified by rank, and then, assuming that each groups correlations fall on a straight line, explain them by a mathematical regression equation.

5.4 Summary

I. From the equations in chapter 5 it is clear that the different groups of coals have different priority parameters, indicating that at the different stages of maturity, different parameters in the coals would be required to determine coke quality and coking capacity.

II. To characterise coals for coking it is necessary first to establish at the outset which process the coke product is to be used. Secondly classify the coals into their respective rank groups and then to characterise each group individually by the use of equations to predict their potential coking qualities.

CONCLUSION

I. Seventeen coals were selected from three different countries and of various ranks and with different rheological properties.

II. A full suite of chemical, rheological, physical and petrographic analysis and tests were undertaken on both the coals and their resulting cokes.

III. Results indicated that the coals could be subdivided into three rank categories, as defined by vitrinite reflectance all falling with in the Bituminous range of rank and most falling in the prime coking range.

IV. Further assessment and observations based on detailed correlations illustrated the following:

   a) That the resolidification temperature of the coal determines the amount and the percentage of the different anisotropic carbon forms in the binder phase of the coke.
   b) That the resolidification temperature could be linked to rank, which showed an increase as the rank increased and a decrease as the rank of the coal moved into to semi anthracite range.
   c) This in turn influenced the mechanical and chemical properties of the resulting coke.
   d) Isotropic carbon in the binder phase as determined by, petrographic analyses of the coke resulted in weaker coke with higher CO_2 reactivity, and anisotropic carbon in stronger and less reactive coke.
   e) Certain anisotropic carbon forms in coke especially the ribbon flow type originating from high ranking parent coals appears to be isotropic with regard to their reactivity, white maintaining high cold strength, which is associated with anisotropic carbon forms in the binder phase.
   f) Coal parameters influencing the resulting coke quality differ as the rank of the parent coal increase, and by grouping coals by rank more accurate predictions could be made.

RECOMMENDATIONS

I. Coals in Group 3 should be considered for further testing to try and determine whether or not the anisotropic coke in the binder phase is really anisotropic or is only anisotropic on a macro scale and isotropic on the molecular scale. The suggested method would be the use of Raman microscopy. This method may also explain abnormalities with regard to the other coal groups and could be advantageous to our understanding of the coking process at all levels of development.

II. In summary it is recommended that the principles and formulas proposed in this project report should (a) be tested further on a wider range of coals in order to test validity on a wider scale and (b) be incorporated into the prediction methods of cokability performance when blending a number of different coals. Such steps would also lead to establishing whether the principles of additive or non-additive predictions and calculations can be applied to blended coals in future.

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APPENDIX 1

Table 1 Chemical and Petrographic Properties

APPENDIX 1 **PROPERTIES**		**Twin Rock Mid Vol Coking Coal**	**Knox Creek Coking Coal**	**Shoal Creek Coking Coal**	**Arch Export Blend Coking Coal**
<u>Chemical Properties</u>:					
Moisture (adb)	%	0.6	0.7	0.7	1.1
Ash (db)	%	9.2	10.8	10.3	5.6
Volatile Matter (db)	%	24.1	32.7	25.9	35.6
Total Sulphur (db)	%	1.24	0.61	0.92	0.83
Pyritic Sulphur	%	0.64	0.08	0.25	0.17
Sulphate Sulphur	%	0.06	0.01	-	-
Organic Sulphur	%	0.54	0.52	0.67	0.66
Carbon (db)	%	80.1	77.5	75.0	82.5
Hydrogen (db)	%	4.55	4.80	4.60	5.08
Nitrogen (db)	%	1.39	1.34	1.61	1.51
Oxygen (db)	%	3.50	4.98	7.53	4.48
Fixed Carbon (calc. adb)	%	66.3	56.2	63.4	58.2
Gross Calorific. Value (adb)	MJ/kg	32.88	31.78	32.43	33.39
Free Swelling Index		9.0	8.0	8.5	8.0
Roga Index		88	82	87	91
<u>Petrographic Properties</u>:					
<u>Maceral Composition</u>:					
Vitrinite	%	85.9	58.1	76.1	67.3
Liptinite (Exinite)	%		8.1	1.1	9.5
Reactive Semifusinite	%	1.2	11.6	4.5	6.1
Inertinite	%	7.6	16.2	12.5	13.8
Mineral Matter	%	5.3	6.0	5.8	3.3
<u>Vitrinite Reflectance Classes</u>:					
V7 (0.70 to 0.79)	%		2 (1.3)		5 (3.8)
V8 (0.80 to 0.89)	%		18 (11.9)		23 (17.7)
V9 (0.90 to 0.99)	%		40 (26.5)		41 (31.5)
V10 (1.00 to 1.09)	%		32 (21.4)	4 (3.1)	27 (21.0)
V11 (1.10 to 1.19)	%	8 (6.9)	8 (7.4)	40 (30.9)	4 (4.5)
V12 (1.20 to 1.29)	%	22 (18.9)	(4.7)	41 (31.7)	(2.5)
V13 (1.30 to 1.39)	%	58 (49.8)	(3.7)	15 (11.8)	(1.7)
V14 (1.40 to 1.49)	%	12 (10.4)	(0.9)	(1.8)	(0.2)
V15 (1.50 to 1.59)	%	(0.3)		(1.8)	
<u>Petrographic Parameters</u>:					
RoV (max)	%	1.32	0.98	1.22	0.95
RoR	%	1.33	1.02	1.23	0.97
Total Reactives	%	86.3	77.8	81.0	82.9
Total Inerts	%	13.7	22.2	19.0	17.1
Optimum Inerts	%	19.5	19.3	22.3	20.0
Composition Balance Index		0.70	1.15	0.85	0.86

( ): Distribution of reactives in reflectance classes.

Table 2 Physical Rheological and Coal Ash Properties

PROPERTIES		**Twin Rock Mid Vo Coking Coal**	**Knox Creek Coking Coal**	**Shoal Creek Coking Coal**	**Arch Export Blend Coking Coal**
Physical Properties:					
Hardgrove Index		98	55	82	48
Rheological Properties:					
Dilatation:					
Softening Temp.	ºC	377	347	365	351
Maximum Contraction Temp.	ºC	416	406	408	404
Maximum Dilatation Temp.	ºC	479	455	473	446
Maximum Contraction	%	29	34	31	33
Maximum Dilatation	%	178	109	186	91
Amplitude	%	207	143	217	124
Gieseler Fluidity:					
Initial Softening Temp.	ºC	426	410	420	411
Maximum Fluidity Temp.	ºC	469	447	467	444
Resolidification Temp.	ºC	508	486	503	480
Maximum Fluidity	ddpm	1685	11042	2665	6352
Coal Ash Properties:					
Ash Composition:					
SiO_2	%	49.35	50.25	49.45	52.36
Al_2O_3	%	29.50	23.96	30.45	27.68
Fe_2O_3	%	11.86	6.60	7.40	8.58
TiO_2	%	1.36	1.75	1.52	1.67
P_2O_5	%	0.42	0.44	0.99	0.23
CaO	%	2.13	7.98	2.44	1.96
MgO	%	0.89	1.23	1.37	1.15
Na_2O	%	0.24	0.43	0.89	0.75
K_2O	%	2.01	1.49	2.17	2.22
SO_3	%	1.31	3.84	1.55	1.50
MnO	%	0.01	0.04	0.03	0.02
Ba	%	0.06	0.08	0.25	0.15
Sr	%	0.09	0.13	0.18	0.21
V_2O_5	%	0.04	0.03	0.05	0.05
Cr_2O_3	%	0.02	0.01	0.01	0.01
ZrO_2	%	0.03	0.05	0.07	0.07
Total	%	99.32	98.31	98.82	98.61
Ash Fusion Temperatures:					
Initial Temp.	°C	1347	1265	1397	1385
Softening Temp.	°C	1371	1278	1418	1416
Hemisphere Temp.	°C	1423	1289	>1550	1440
Flow Temp.	°C	1521	1309	>1550	1500

Table 3 Chemical and Petrographic Properties

PROPERTIES		Oak Grove Coking Coal	Alpha Amfire Coking Coal	Kepler Low Vol Coking Coal
Chemical Properties:				
Moisture (adb)	%	0.7	0.8	0.6
Ash (db)	%	8.9	8.4	5.4
Volatile Matter (db)	%	20.3	19.2	19.0
Total Sulphur (db)	%	0.51	1.35	0.74
Pyritic Sulphur	%	0.03	0.49	0.17
Sulphate Sulphur	%	-	0.03	0.03
Organic Sulphur	%	0.48	0.83	0.54
Carbon (db)	%	82.6	83.1	84.0
Hydrogen (db)	%	4.49	4.44	4.54
Nitrogen (db)	%	1.72	1.37	1.48
Oxygen (db)	%	1.74	1.38	3.80
Fixed Carbon (calc. adb)	%	70.2	71.8	75.2
Gross Calorific. Value (adb)	MJ/kg	33.15	33.27	34.55
Free Swelling Index		8.0	9.0	8.0
Roga Index		85	82	74
Petrographic Properties:				
Maceral Composition:				
Vitrinite	%	68.6	85.0	81.0
Liptinite (Exinite)	%			
Reactive Semifusinite	%	7.9	1.7	3.0
Inertinite	%	18.6	8.4	12.9
Mineral Matter	%	4.9	4.9	3.1
Vitrinite Reflectance Classes:				
V13 (1.30 to 1.39)	%	23 (15.8)	2 (1.7)	7 (5.7)
V14 (1.40 to 1.49)	%	49 (33.6)	17 (14.4)	10 (8.1)
V15 (1.50 to 1.59)	%	25 (17.2)	42 (35.7)	36 (29.2)
V16 (1.60 to 1.69)	%	3 (2.0)	30 (25.5)	34 (27.5)
V17 (1.70 to 1.79)	%		8 (6.8)	12 (9.7)
V18 (1.80 to 1.89)	%		1 (0.9)	1 (0.8)
Petrographic Parameters:				
RoV (max)	%	1.46	1.58	1.59
RoR	%	1.46	1.58	1.59
Total Reactives	%	68.6	85.0	81.0
Total Inerts	%	31.4	15.0	19.0
Optimum Inerts	%	8.1	5.1	5.0
Composition Balance Index		3.88	2.94	3.80

( ): Distribution of reactives in reflectance classes.

Table 4 Physical Rheological and Coal Ash Properties

PROPERTIES		Oak Grove Coking Coal	Alpha Amfire Coking Coal	Kepler Low Vol Coking Coal
Physical Properties:				
Hardgrove Index		93	107	100
Rheological Properties:				
Dilatation:				
Softening Temp.	ºC	405	422	416
Maximum Contraction Temp.	ºC	436	452	443
Maximum Dilatation Temp.	ºC	482	489	482
Maximum Contraction	%	24	23	22
Maximum Dilatation	%	73	17	50
Amplitude	%	97	40	72
Gieseler Fluidity:				
Initial Softening Temp.	ºC	444	455	457
Maximum Fluidity Temp.	ºC	479	486	486
Resolidification Temp.	ºC	508	499	510
Maximum Fluidity	ddpm	285	7	70
Coal Ash Properties:				
Ash Composition:				
SiO_2	%	50.53	43.00	48.86
Al_2O_3	%	33.29	28.25	31.32
Fe_2O_3	%	4.60	14.15	9.17
TiO_2	%	1.84	1.29	1.49
P_2O_5	%	0.94	0.56	0.34
CaO	%	2.67	3.86	2.12
MgO	%	1.11	1.07	1.27
Na_2O	%	0.34	0.26	0.66
K_2O	%	1.68	1.70	2.18
SO_3	%	0.79	4.06	0.79
MnO	%	0.02	0.02	0.03
Ba	%	0.14	0.07	0.08
Sr	%	0.16	0.12	0.12
V_2O_5	%	0.06	0.05	0.08
Cr_2O_3	%	0.01	0.02	0.02
ZrO_2	%	0.07	0.03	0.08
Total	%	98.25	98.51	98.61
Ash Fusion Temperatures:				
Initial Temp.	°C	>1550	1306	1475
Softening Temp.	°C	>1550	1314	1510
Hemisphere Temp.	°C	>1550	1338	>1550
Flow Temp.	°C	>1550	1513	>1550

Table 5 Chemical and Petrographic Properties

PROPERTIES		**Blue Creek No.4**	**Blue Creek No.7**	**Pinnacle**
Chemical Properties:				
Moisture (adb)	%	0.7	0.7	0.5
Ash (db)	%	8.5	8.4	6.1
Volatile Matter (db)	%	29.1	19.9	16.2
Total Sulphur (db)	%	0.73	0.60	0.81
Pyritic Sulphur	%	0.18	0.07	0.21
Sulphate Sulphur	%	0.01	-	0.02
Organic Sulphur	%	0.54	0.53	0.58
Carbon (db)	%	81.2	82.7	86.5
Hydrogen (db)	%	4.77	4.35	4.18
Nitrogen (db)	%	1.75	1.60	1.18
Oxygen (db)	%	3.00	2.35	1.23
Fixed Carbon (calc. adb)	%	61.9	71.2	77.3
Gross Calorific. Value (adb)	MJ/kg	32.83	33.33	34.20
Free Swelling Index		9.0	9.0	7.0
Roga Index		89	88	74
Petrographic Properties:				
Maceral Composition:				
Vitrinite	%	82.6	78.0	74.3
Liptinite (Exinite)	%	2.5		
Reactive Semifusinite	%	1.9	4.5	5.6
Inertinite	%	8.2	12.8	16.6
Mineral Matter	%	4.8	4.7	3.5
Vitrinite Reflectance Classes:				
V7 (0.70 to 0.79)	%			
V8 (0.80 to 0.89)	%			
V9 (0.90 to 0.99)	%	1 (0.8)		
V10 (1.00 to 1.09)	%	33 (28.1)		
V11 (1.10 to 1.19)	%	55 (46.8)		
V12 (1.20 to 1.29)	%	11 (9.4)		
V13 (1.30 to 1.39)	%	(0.6)	8 (6.3)	
V14 (1.40 to 1.49)	%	(1.1)	59 (46.0)	2 (1.5)
V15 (1.50 to 1.59)	%	(0.2)	29 (22.6)	13 (9.7)
V16 (1.60 to 1.69)	%		3 (2.3)	37 (27.5)
V17 (1.70 to 1.79)	%		1 (0.8)	40 (29.7)
V18 (1.80 to 1.89)	%			4 (3.0)
V18+	%			4
Petrographic Parameters:				
RoV (max)	%	1.13	1.48	1.69
RoR	%	1.13	1.48	1.68
Total Reactives	%	87.0	78.0	71.4
Total Inerts	%	13.0	22.0	28.6
Optimum Inerts	%	24.9	7.8	2.6
Composition Balance Index		0.52	2.82	11.0

( ): Distribution of reactives in reflectance classes

Table 6 Physical Rheological and Coal Ash Properties

PROPERTIES		Blue Creek No.4	Blue Creek No.7	Pinnacle
Physical Properties:				
Hardgrove Index		75	94	98
Rheological Properties:				
Dilatation:				
Softening Temp.	ºC	365	412	435
Maximum Contraction Temp.	ºC	401	434	464
Maximum Dilatation Temp.	ºC	477	489	494
Maximum Contraction	%	30	29	30
Maximum Dilatation	%	254	108	5
Amplitude	%	284	137	35
Gieseler Fluidity:				
Initial Softening Temp.	ºC	412	446	477
Maximum Fluidity Temp.	ºC	457	482	488
Resolidification Temp.	ºC	500	518	504
Maximum Fluidity	ddpm	22528	763	4
Coal Ash Properties:				
Ash Composition:				
SiO_2	%	48.32	49.65	50.56
Al_2O_3	%	28.93	29.80	29.18
Fe_2O_3	%	8.27	7.57	8.46
TiO_2	%	1.51	1.59	1.88
P_2O_5	%	1.30	0.70	0.39
CaO	%	3.10	2.75	3.28
MgO	%	1.42	1.09	0.98
Na_2O	%	0.79	0.47	0.93
K_2O	%	2.27	1.86	1.10
SO_3	%	1.90	1.22	2.15
MnO	%	0.03	0.03	0.03
Ba	%	0.38	0.21	0.07
Sr	%	0.26	0.15	0.13
V_2O_5	%	0.05	0.06	0.03
Cr_2O_3	%	0.01	0.01	0.01
ZrO_2	%	0.07	0.06	0.07
Total	%	98.61	97.22	99.25
Ash Fusion Temperatures:				
Initial Temp.	°C	1433	1507	1426
Softening Temp.	°C	1447	1524	1444
Hemisphere Temp.	°C	1488	>1550	1470
Flow Temp.	°C	1496	>1550	1505

Table 7 Chemical and Petrographic Properties

PROPERTIES		Marfolk Eagle	Wells	Cedar Grove
Chemical Properties:				
Moisture (adb)	%	0.9	1.1	1.0
Ash (db)	%	6.1	5.9	6.0
Volatile Matter (db)	%	32.7	34.3	33.1
Total Sulphur (db)	%	0.93	0.82	0.92
Pyritic Sulphur	%	0.17	0.16	0.12
Sulphate Sulphur	%	0.04	0.01	0.09
Organic Sulphur	%	0.72	0.65	0.71
Carbon (db)	%	83.5	82.6	83.3
Hydrogen (db)	%	5.04	5.04	5.03
Nitrogen (db)	%	1.50	1.47	1.51
Oxygen (db)	%	2.96	4.12	3.29
Fixed Carbon (calc. adb)	%	60.6	59.2	60.2
Gross Calorific. Value (adb)	MJ/kg	33.87	33.27	32.78
Free Swelling Index		9.0	8.5	8.5
Roga Index		89	85	87
Petrographic Properties:				
Maceral Composition:				
Vitrinite	%	77.0	70.9	74.4
Liptinite (Exinite)	%	5.4	8.1	5.6
Reactive Semifusinite	%	3.3	5.0	4.0
Inertinite	%	10.8	12.6	12.5
Mineral Matter	%	3.5	3.4	3.5
Vitrinite Reflectance Classes:				
V7 (0.70 to 0.79)	%			1 (0.8)
V8 (0.80 to 0.89)	%	4 (3.3)	6 (4.7)	6 (4.8)
V9 (0.90 to 0.99)	%	13 (10.7)	44 (34.8)	29 (23.2)
V10 (1.00 to 1.09)	%	33 (27.2)	44 (34.8)	36 (28.8)
V11 (1.10 to 1.19)	%	38 (31.4)	6 (5.0)	23 (18.6)
V12 (1.20 to 1.29)	%	12 (10.3)	(2.2)	5 (5.2)
V13 (1.30 to 1.39)	%	(1.1)	(2.2)	(1.5)
V14 (1.40 to 1.49)	%	(1.3)	(0.3)	(0.9)
V15 (1.50 to 1.59)	%	(0.4)		(0.2)
V16 (1.60 to 1.69)	%			
V17 (1.70 to 1.79)	%			
V18 (1.80 to 1.89)	%			
V18+	%			
Petrographic Parameters:				
RoV (max)	%	1.09	1.00	1.04
RoR	%	1.10	1.02	1.05
Total Reactives	%	85.7	84.0	84.0
Total Inerts	%	14.3	16.0	16.0
Optimum Inerts	%	23.5	21.4	22.0
Composition Balance Index		0.61	0.75	0.73

( ): Distribution of reactives in reflectance classes.

Table 8 Physical Rheological and Coal Ash Properties

PROPERTIES		**Marfolk Eagle**	**Wells**	**Cedar Grove**
Physical Properties:				
Hardgrove Index		73	50	70
Rheological Properties:				
Dilatation:				
Softening Temp.	ºC	354	355	347
Maximum Contraction Temp.	ºC	401	407	403
Maximum Dilatation Temp.	ºC	465	456	471
Maximum Contraction	%	31	33	32
Maximum Dilatation	%	259	119	239
Amplitude	%	290	152	271
Gieseler Fluidity:				
Initial Softening Temp.	ºC	404	410	402
Maximum Fluidity Temp.	ºC	447	446	440
Resolidification Temp.	ºC	497	485	490
Maximum Fluidity	ddpm	35711	27029	34673
Coal Ash Properties:				
Ash Composition:				
SiO_2	%	54.40	51.14	52.98
Al_2O_3	%	27.79	31.39	30.11
Fe_2O_3	%	8.60	7.17	8.80
TiO_2	%	1.45	1.55	1.46
P_2O_5	%	0.08	0.10	0.11
CaO	%	1.03	1.76	1.05
MgO	%	1.08	0.87	0.91
Na_2O	%	0.49	0.45	0.52
K_2O	%	2.62	1.90	1.92
SO_3	%	1.07	1.53	0.11
MnO	%	0.01	0.04	0.02
Ba	%	0.08	0.06	0.13
Sr	%	0.09	0.09	0.12
V_2O_5	%	0.05	0.05	0.06
Cr_2O_3	%	0.01	0.01	0.01
ZrO_2	%	0.05	0.04	0.05
Total	%	98.90	98.15	98.36
Ash Fusion Temperatures:				
Initial Temp.	°C	1447	>1550	1489
Softening Temp.	°C	1472	>1550	1531
Hemisphere Temp.	°C	1499	>1550	>1550
Flow Temp.	°C	1542	>1550	>1550

Table 9 Chemical and Petrographic Properties

PROPERTIES		Riverside / Goonyella	Oaky North	Grootegeluk	Tshikondeni
Chemical Properties:					
Moisture (adb)	%	0.5	0.5	2.2	0.4
Ash (db)	%	8.5	9.7	9.5	13.3
Volatile Matter (db)	%	24.3	24.0	3.81	20.1
Total Sulphur (db)	%	0.51	0.56	0.94	0.73
Pyritic Sulphur	%	0.02	0.10	0.14	0.13
Sulphate Sulphur	%	0.01	0.03	0.01	0.01
Organic Sulphur	%	0.48	0.43	0.79	0.59
Carbon (db)	%	82.4	81.8	75.7	80.3
Hydrogen (db)	%	4.52	4.56	4.82	4.23
Nitrogen (db)	%	1.71	1.92	1.38	1.79
Oxygen (db)	%	2.41	1.50	7.63	0.73
Fixed Carbon (calc. adb)	%	66.8	65.9	51.3	66.8
Gross Calorific. Value (adb)	MJ/kg	32.79	32.81	29.84	31.87
Free Swelling Index		9.0	9.0	6.0	9.0
Roga Index		80	84	78	87
Petrographic Properties:					
Maceral Composition:					
Vitrinite	%	59.5	78.7	88.5	81.1
Liptinite (Exinite)	%	-	-	1.9	-
Reactive Semifusinite	%	16.8	3.7	0.7	2.4
Inertinite	%	19.0	12.2	3.5	9.1
Mineral Matter	%	4.7	5.4	5.4	7.4
Vitrinite Reflectance Classes:					
V6 (0.60 to 0.69)	%			26 (23.5)	
V7 (0.70 to 0.79)	%			54 (48.8)	
V8 (0.80 to 0.89)	%			20 (18.1)	
V9 (0.90 to 0.99)	%			(0.2)	
V10 (1.00 to 1.09)	%	19 (11.3)		(0.4)	
V11 (1.10 to 1.19)	%	32 (19.0)	13 (10.2)	(0.1)	
V12 (1.20 to 1.29)	%	42 (35.5)	41 (32.3)		1 (0.8)
V13 (1.30 to 1.39)	%	7 (7.4)	39 (30.7)		15 (12.2)
V14 (1.40 to 1.49)	%	(5.4)	7 (6.0)		37 (30)
V15 (1.50 to 1.59)	%	(7.0)	(1.5)		39 (31.6)
V16 (1.60 to 1.69)	%				8 (6.5)
V17 (1.70 to 1.79)	%				
V18 (1.80 to 1.89)	%				
V18+	%				
Petrographic Parameters:					
RoV (max)	%	1.19	1.29	0.74	1.49
RoR	%	1.25	1.30	0.75	1.49
Total Reactives	%	75.1	80.7	91.1	81.1
Total Inerts	%	24.9	19.3	8.9	18.9
Optimum Inerts	%	18.9	20.1	17.5	8.2
Composition Balance Index		1.32	0.96	0.51	2.3

Table 10 Physical Rheological and Coal Ash Properties

Properties	Riverside/ Goonyella	Oaky North	Grootegeluk	Tshikondeni
Physical Properties:				
Hardgrove Index	88	93	53	-
Rheological Properties:				
Dilatation:				
Softening Temp. ºC	395	390	369	394
Max Contraction Temp. ºC	431	422	407	424
Max Dilatation Temp. ºC	471	480	437	481
Max Contraction %	26	29	36	25
Max Dilatation %	54	127	22	129
Amplitude %	80	156	58	154
Gieseler Fluidity:				
Initial Softening Temp. ºC	435	427	411	435
Max Fluidity Temp. ºC	466	469	436	479
Resolidification Temp. ºC	500	502	455	515
Max Fluidity ddpm	588	861	34	1356
Coal Ash Properties:				
Ash Composition:				
SiO_2 %	63.11	51.97	66.62	54.11
Al_2O_3 %	28.19	32.02	18.62	24.67
Fe_2O_3 %	3.21	5.40	5.72	5.39
TiO_2 %	1.77	1.66	2.24	1.58
P_2O_5 %	0.38	1.42	0.12	0.70
CaO %	0.53	2.16	1.55	3.78
MgO %	0.59	0.97	0.81	1.86
Na_2O %	0.41	0.77	0.18	0.47
K_2O %	0.85	1.18	1.04	1.30
SO_3 %	0.12	0.58	1.37	3.31
MnO %	0.03	0.04	0.07	0.05
Ba %	0.03	0.06	0.06	0.24
Sr %	0.06	0.14	0.04	0.17
V_2O_5 %	0.06	0.06	0.17	0.03
Cr_2O_3 %	ND	ND	0.03	ND
ZrO_2 %	0.14	0.12	0.26	0.11
Total %	99.48	98.55	98.90	97.77
Ash Fusion Temperatures:				
Initial Temp. °C	1540	>1550	1370	1318
Softening Temp. °C	>1550	>1550	1398	1352
Hemisphere Temp. °C	>1550	>1550	1425	1425
Flow Temp. °C	>1550	>1550	1471	1453

Table 11 Coke Petrographic Composition: Textural component Analyses

SAMPLE CODES	**1 175022 TWIN ROCK**	**2 179030 KNOX CREEK**	**3 180024 ARCH EXPORT**	**4 181031 SHOAL CREEK**	**5 182029 AMFIRE**	**6 188030 KEPLER**
CARBON FORMS (Vol. %)						
BINDER PHASE TOTAL :	**80**	**74**	**77**	**83**	**71**	**75**
FILLER PHASE TOTAL :	**20**	**26**	**22**	**17**	**26**	**24**
Organic Inerts						
Fine < 50 microns	4	7	7	5	8	7
Coarse > 50 microns	6	8	8	5	8	9
Miscellaneous Inerts						
Oxidized coal	0	0	0	0	0	0
Non-coking vitrinite	3	< 1	2	1	3	1
Isotropic coke as filler	0	0	0	0	0	0
Inorganic Inerts						
Fine < 50 microns	4	6	3	3	5	4
Coarse > 50 microns	3	5	2	3	2	3
Pyritic Minerals	< 1	< 1	< 1	< 1	< 1	< 1
MISCELLANEOUS MATERIALS TOTAL :	**0**	**0**	**1**	**0**	**3**	**1**
Depositional Carbons						
Sooty	0	0	0	0	0	0
Spherulitic	0	0	0	0	0	0
Pyrolytic	< 1	< 1	1	< 1	< 1	< 1
Additive Carbons	0	0	0	0	0	0
Other						
Green Coke	< 1	< 1	< 1	< 1	3	1
Coal	0	0	0	0	0	0
Contaminating Particles	0	0	0	0	0	0
TOTAL %	**100**	**100**	**100**	**100**	**100**	**100**

Table 12 Coke Petrographic Composition: Textural component Analyses

SAMPLE CODES	**7 189022 OAK GROVE**	**8 193029 BLUE CREEK 4**	**9 194026 BLUE CREEK 7**	**10 195028 PINNACLE**	**11 196023 WELLS**	**12 200029 CEDAR GROVE**	**13 201022 MARFORK**
CARBON FORMS (Vol. %)							
BINDER PHASE TOTAL :	**76**	**82**	**80**	**60**	**80**	**82**	**76**
FILLER PHASE TOTAL :	**24**	**18**	**20**	**40**	**20**	**18**	**16**
Organic Inerts							
Fine < 50 microns	9	6	6	14	9	5	6
Coarse > 50 microns	9	6	7	17	6	6	4
Miscellaneous Inerts							
Oxidized coal	0	0	0	0	0	0	0
Non-coking vitrinite	1	1	2	1	< 1	2	0
Isotropic coke as filler	0	0	0	0	0	0	0
Inorganic Inerts							
Fine < 50 microns	3	3	3	4	3	3	3
Coarse > 50 microns	2	2	2	4	2	2	3
Pyritic Minerals	< 1	< 1	< 1	< 1	< 1	< 1	< 1
MISCELLANEOUS MATERIALS TOTAL :	**0**	**0**	**0**	**0**	**0**	**0**	**8**
Depositional Carbons							
Sooty	0	0	0	0	0	0	0
Spherulitic	0	0	0	0	0	0	0
Pyrolytic	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Additive Carbons	0	0	0	0	0	0	0
Other							
Green Coke	< 1	< 1	< 1	< 1	< 1	< 1	8
Coal	0	0	0	0	0	0	0
Contaminating Particles	0	0	0	0	0	0	0
TOTAL %	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note:

Table 13 Coke Petrographic Composition: Textural component Analyses

SAMPLE CODES	**14** **185028** **RGB**	**15** **186025** **OAKY NORTH**	**16** **202023** **GROOTEGELUK**	**17** **241012** **TSHIKONDENI**
CARBON FORMS (Vol. %)				
BINDER PHASE TOTAL :	**61**	**82**	**82**	**76**
FILLER PHASE TOTAL :	**39**	**18**	**17**	**22**
Organic Inerts				
Fine < 50 microns	17	6	3	7
Coarse > 50 microns	15	7	3	5
Miscellaneous Inerts				
Oxidized coal	0	0	0	0
Non-coking vitrinite	2	1	2	1
Isotropic coke as filler	0	0	1	1
Inorganic Inerts				
Fine < 50 microns	3	2	6	4
Coarse > 50 microns	2	2	2	4
Pyritic Minerals	< 1	< 1	< 1	< 1
MISCELLANEOUS MATERIALS TOTAL :	**0**	**0**	**1**	**2**
Depositional Carbons				
Sooty	0	0	0	0
Spherulitic	0	0	0	0
Pyrolytic	< 1	< 1	1	< 1
Additive Carbons	0	0	0	0
Other				
Green Coke	< 1	< 1	< 1	2
Coal	0	0	0	0
Contaminating Particles	0	0	0	0
TOTAL %	**100**	**100**	**100**	**100**

Table 14 Coke-Distribution of Binder Phase Forms: Textural Component Analyses

SAMPLE CODES	1 175022 TWIN ROCK		2 179030 KNOX CREEK		3 180024 ARCH EXPORT		4 181031 SHOAL CREEK		5 182029 AMFIRE		6 188030 KEPLER	
CARBON FORMS (Vol. %)												
BINDER PHASE												
METALLURGICAL COKE												
Isotropic (from V 7 or lower)	**2**		**11**		**19**		**1**		**1**		**0**	
		3		**40**		**57**		**1**		**1**		**0**
Incipient Anisotropic (from V 8)	**1**		**29**		**38**		**0**		**0**		**0**	
Circular Anisotropic (Granular)												
Fine (from V 9) 0.5 - 1.0 microns	**1**		**48**		**40**		**1**		**1**		**1**	
Medium (from V 10) 1.0 - 1.5 microns	**3**	**17**	**6**	**57**	**2**	**43**	**3**	**26**	**2**	**6**	**1**	**3**
Coarse (from V 11) 1.5 - 2.0 microns	**13**		**3**		**1**		**22**		**3**		**1**	
Lenticular (Leaflet) Anisotropic												
Fine (from V 12) width 1 - 3 microns	**36**		**2**		**0**		**40**		**6**		**2**	
Medium (from V 13) width 3 - 8 microns	**31**	**78**	**1**	**3**	**0**	**0**	**26**	**72**	**4**	**19**	**10**	**28**
Coarse (from V 14) width 8 - 12 microns	**11**		**0**		**0**		**6**		**9**		**16**	
Ribbon (Flow) Anisotropic												
Fine (from V 15) length 2 - 12 microns	**2**		**0**		**0**		**1**		**37**		**50**	
Medium (from V 16) length 12 - 25 microns	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**1**	**30**	**74**	**18**	**69**
Coarse (from V 17) length > 25 microns	**0**		**0**		**0**		**0**		**7**		**1**	
TOTAL %	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note:

Table 15 Coke-Distribution of Binder Phase Forms: Textural Component Analyses

SAMPLE CODES	**7 189022 OAK GROVE**		**8 193029 BLUE CREEK 4**		**9 194026 BLUE CREEK 7**		**10 195028 PINNACLE**		**11 196023 WELLS**		**12 200029 CEDAR GROVE**		**13 201022 MARFORK**	
CARBON FORMS (Vol. %)														
BINDER PHASE														
METALLURGICAL COKE														
Isotropic (from V 7 or lower)	**1**	**1**	**1**	**2**	**0**	**0**	**0**	**0**	**2**	**15**	**1**	**3**	**0**	**0**
Incipient Anisotropic (from V 8)	**0**		**1**		**0**		**0**		**13**		**2**		**0**	
Circular Anisotropic (Granular)														
Fine (from V 9) 0.5 - 1.0 microns	**1**		**18**		**1**		**0**		**75**		**31**		**26**	
Medium (from V 10) 1.0 - 1.5 microns	**3**	**12**	**39**	**86**	**1**	**4**	**0**	**1**	**8**	**85**	**58**	**97**	**59**	**98**
Coarse (from V 11) 1.5 - 2.0 microns	**8**		**29**		**2**		**1**		**2**		**8**		**13**	
Lenticular (Leaflet) Anisotropic														
Fine (from V 12) width 1 - 3 microns	**32**		**10**		**8**		**3**		**0**		**0**		**2**	
Medium (from V 13) width 3 - 8 microns	**29**	**78**	**2**	**12**	**26**	**67**	**6**	**20**	**0**	**0**	**0**	**0**	**0**	**2**
Coarse (from V 14) width 8 - 12 microns	**17**		**0**		**33**		**11**		**0**		**0**		**0**	
Ribbon (Flow) Anisotropic														
Fine (from V 15) length 2 - 12 microns	**7**		**0**		**23**		**26**		**0**		**0**		**0**	
Medium (from V 16) length 12 - 25 microns	**2**	**9**	**0**	**0**	**5**	**29**	**36**	**79**	**0**	**0**	**0**	**0**	**0**	**0**
Coarse (from V 17) length > 25 microns	**0**		**0**		**1**		**17**		**0**		**0**		**0**	
TOTAL %	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note:

Table 16 Coke-Distribution of Binder Phase Forms: Textural Component Analyses

SAMPLE CODES	14 185028 RGB PSA 2006 29		15 186025 OAKY NORTH PSA 2006 30		16 202023 GROOTEGELUK PSA 2006 31		17 241012 TSHIKONDENI PSA 2006 28	
CARBON FORMS (Vol. %)								
BINDER PHASE								
METALLURGICAL COKE								
Isotropic (from V 7 or lower)	2	2	2	2	97	98	0	0
Incipient Anisotropic (from V 8)	0		0		1		0	
Circular Anisotropic (Granular)								
Fine (from V 9) 0.5 - 1.0 microns	8		0		1		0	
Medium (from V 10) 1.0 - 1.5 microns	28	75	4	9	1	2	1	6
Coarse (from V 11) 1.5 - 2.0 microns	39		5		0		5	
Lenticular (Leaflet) Anisotropic								
Fine (from V 12) width 1 - 3 microns	18		23		0		32	
Medium (from V 13) width 3 - 8 microns	5	23	39	88	0	0	43	92
Coarse (from V 14) width 8 - 12 microns	0		26		0		17	
Ribbon (Flow) Anisotropic								
Fine (from V 15) length 2 - 12 microns	0		1		0		2	
Medium (from V 16) length 12 - 25 microns	0	0	0	1	0	0	0	2
Coarse (from V 17) length > 25 microns	0		0		0		0	
TOTAL %	100	100	100	100	100	100	100	100

Random Reflectance Histograms of Single Component Cokes

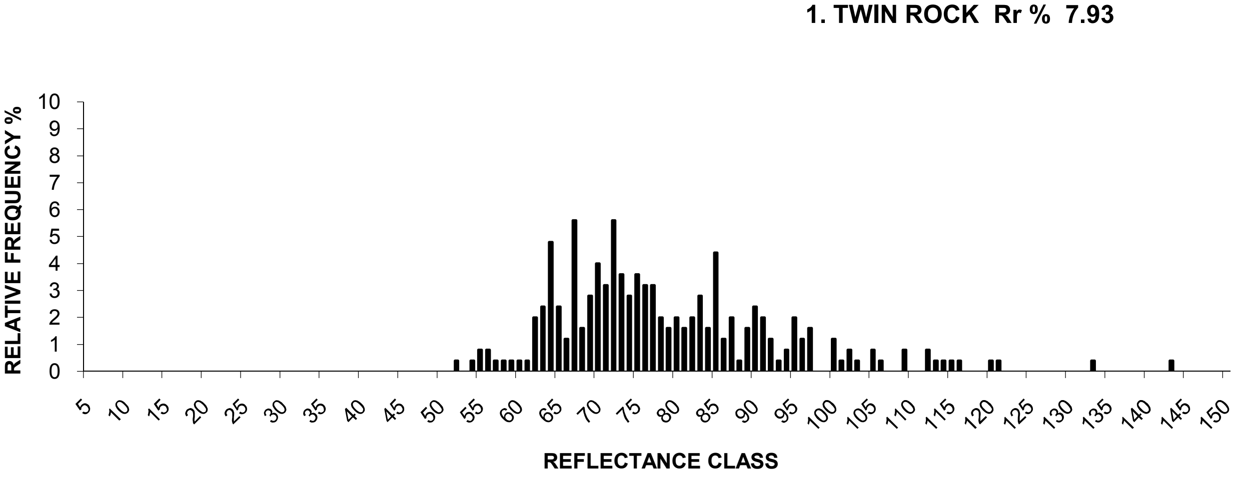

Figure 1 Appendix 1 Twin Rock Coke

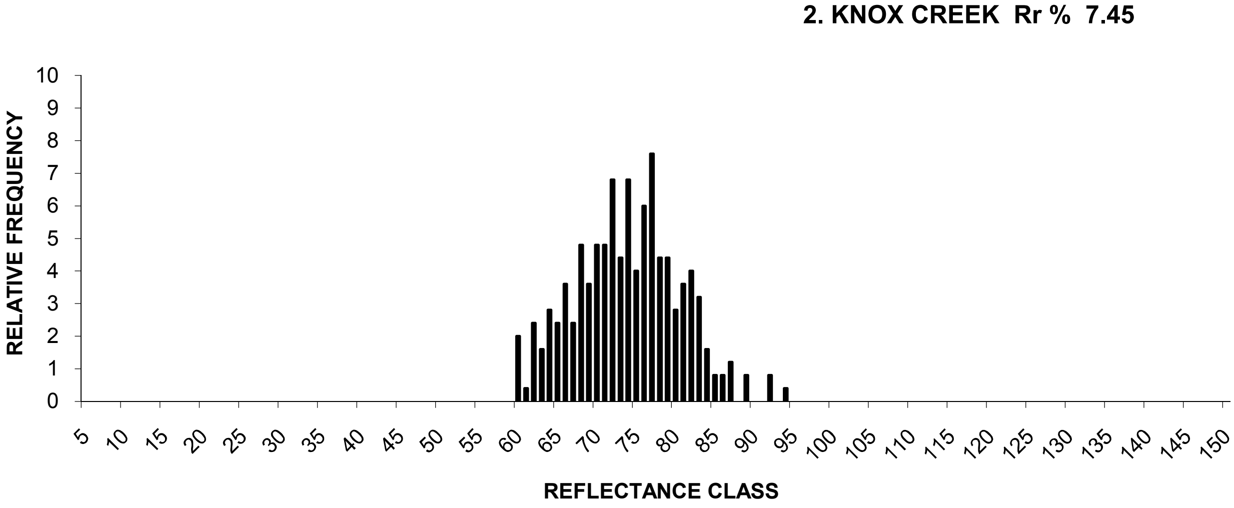

Figure 2 Appendix 1 Knox Creek Coke

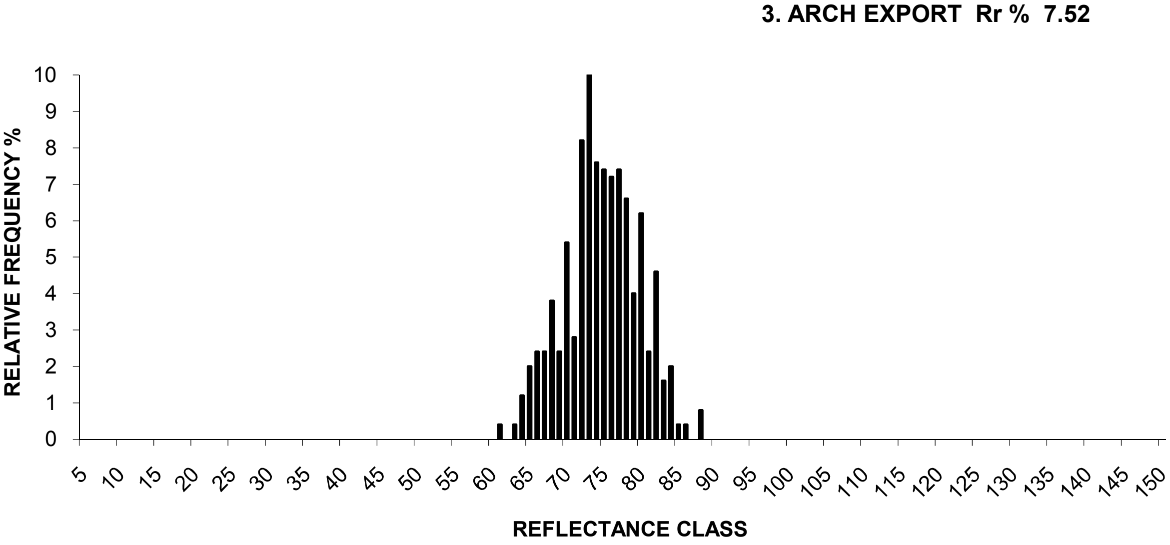

Figure 3 Appendix 1 Arch Export Coke

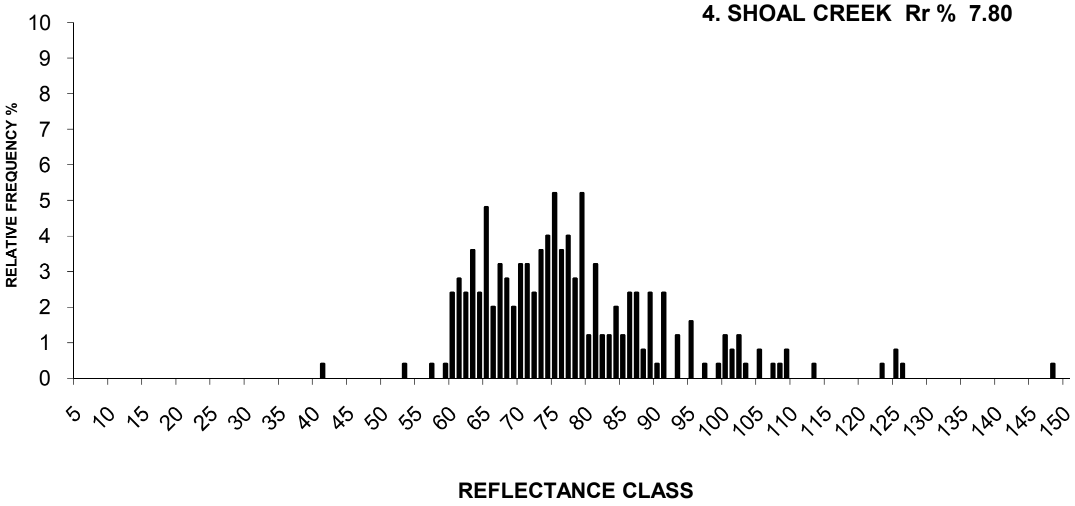

Figure 4 Appendix 1 Shoal Creek Coke

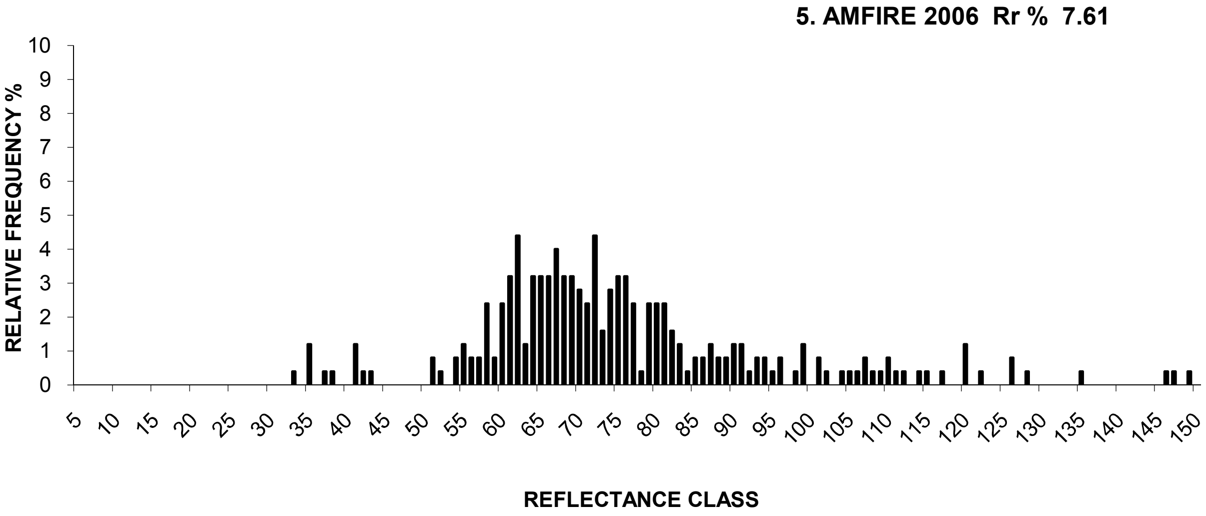

Figure 5 Appendix 1 Amfire Coke

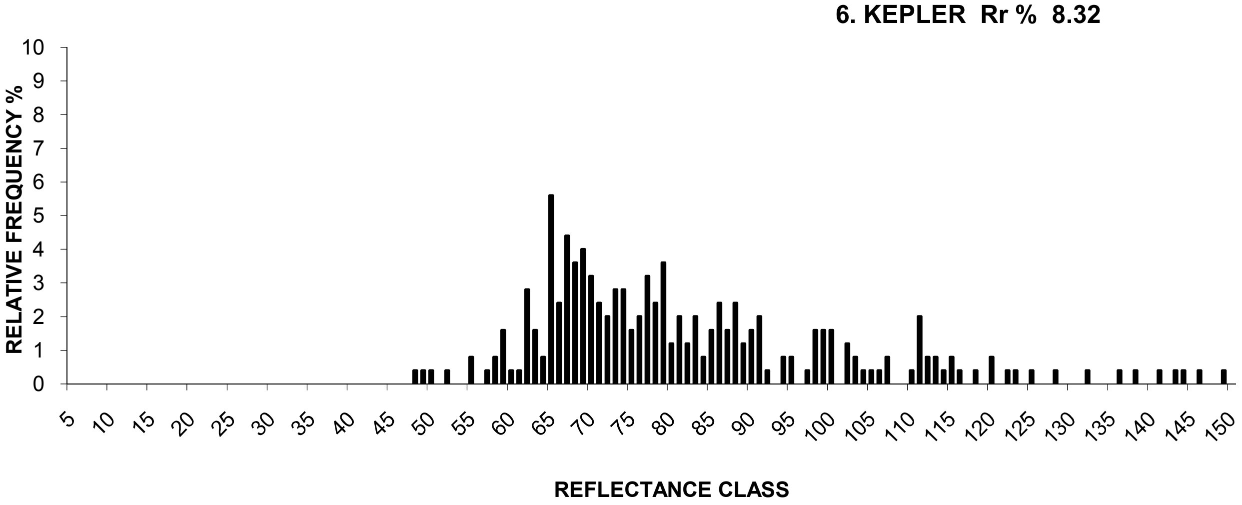

Figure 6 Appendix 1 Kepler Coke

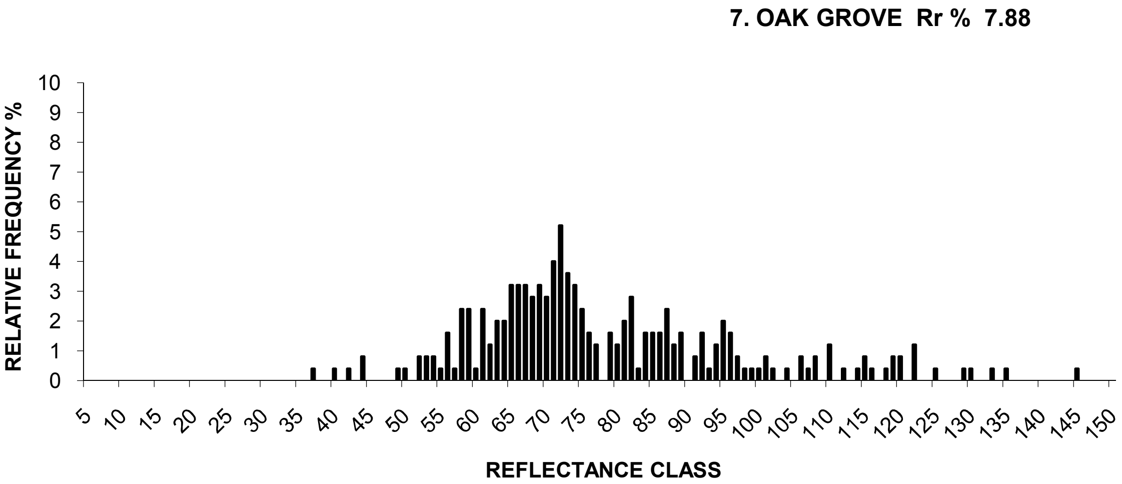

Figure 7 Appendix 1 Oak Grove Coke

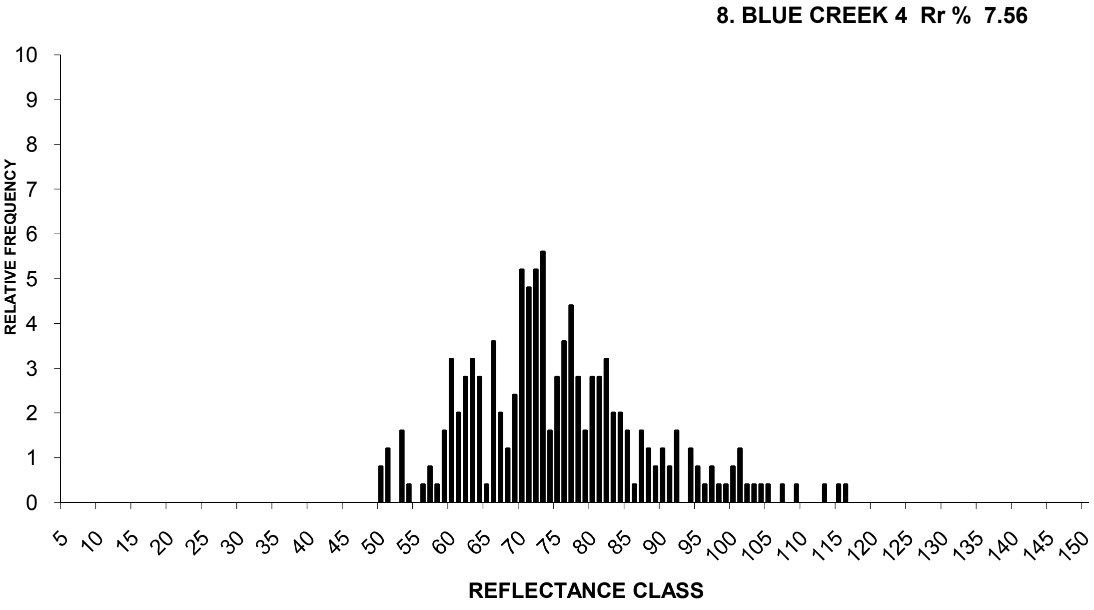

Figure 8 Appendix 1 Blue Creek No. 4 Coke

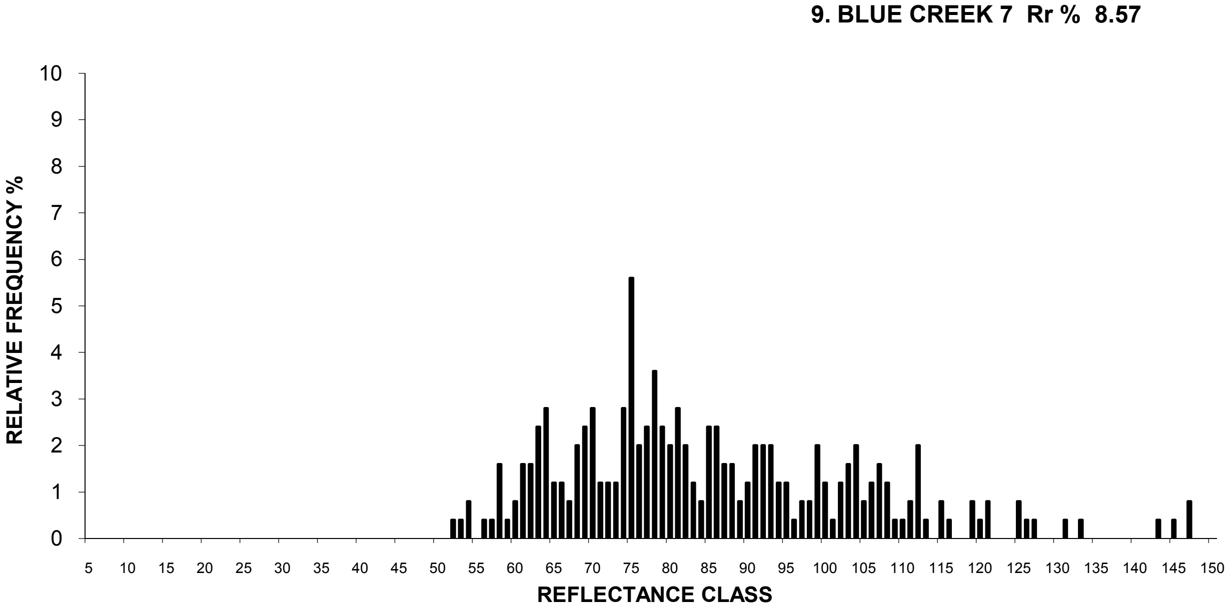

Figure 9 Appendix 1 Blue Creek No. 7 Coke

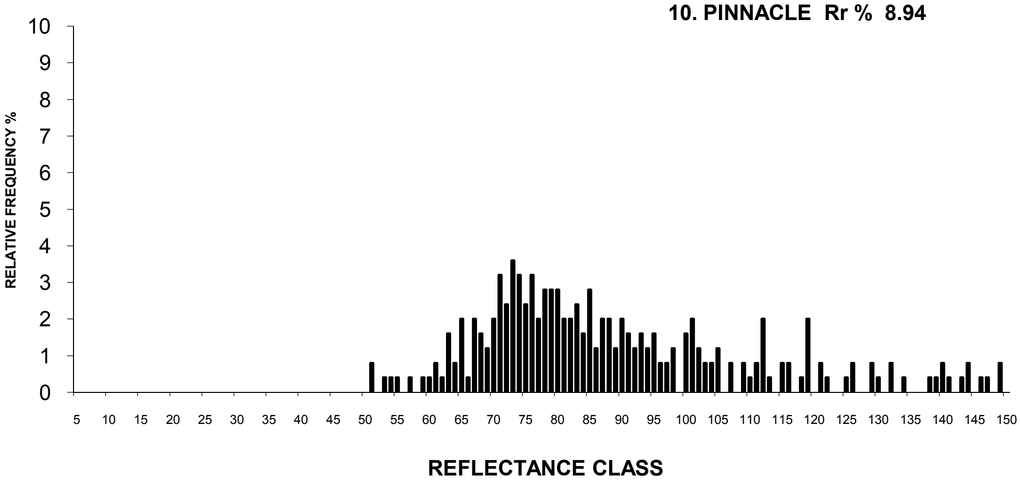

Figure 10 Appendix 1 Pinnacle Coke

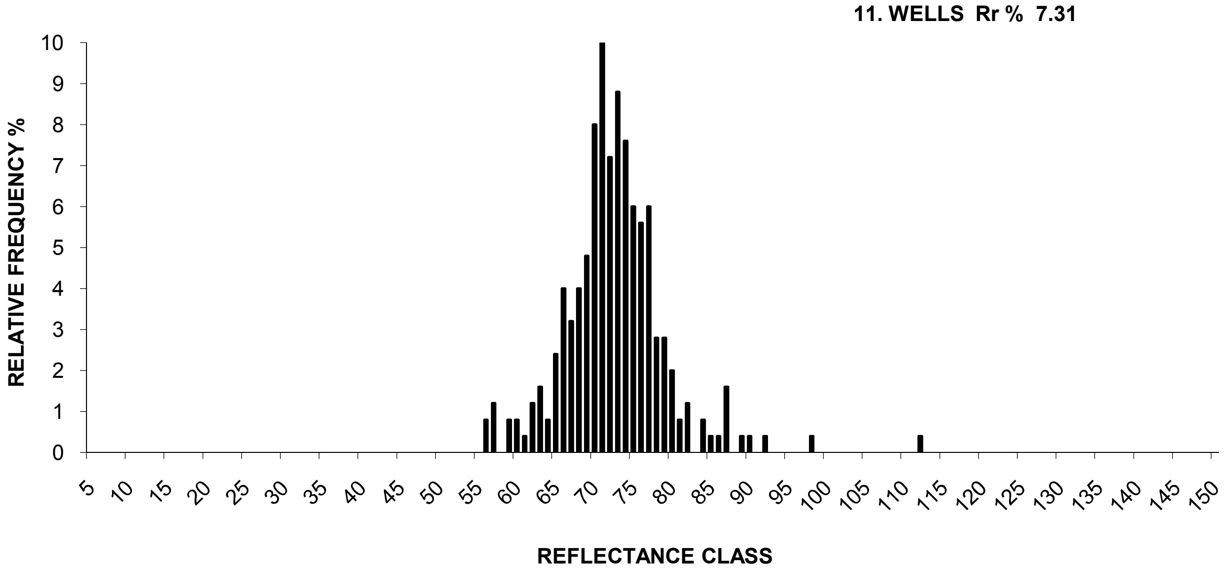

Figure 11 Appendix 1 Wells Coke

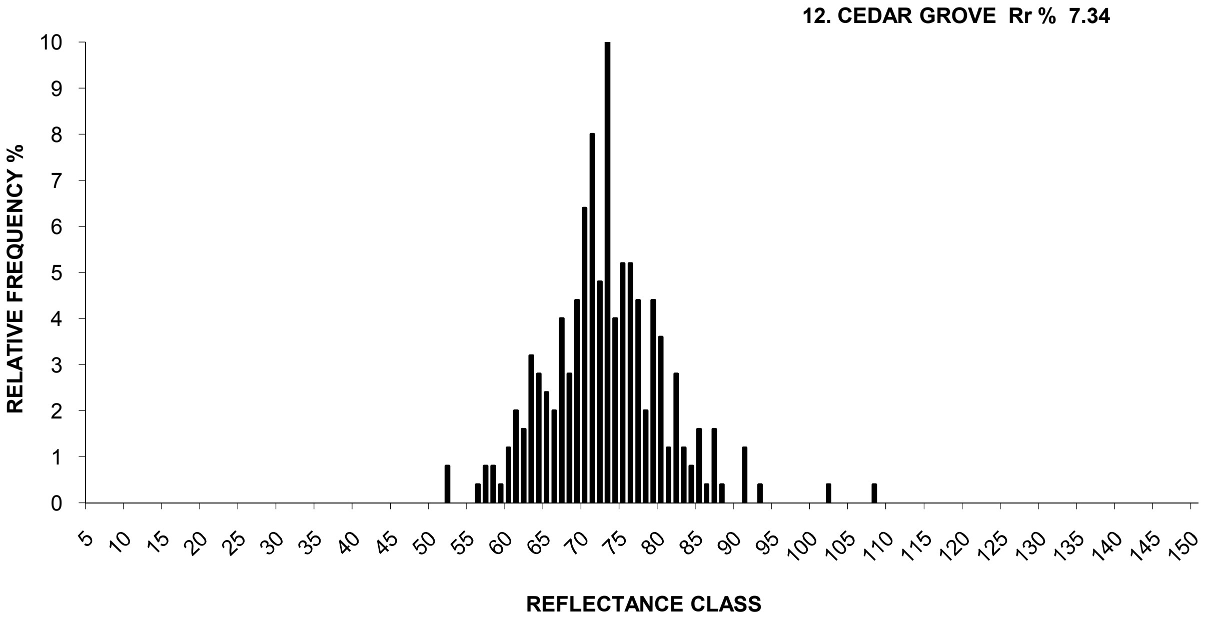

Figure 12 Appendix 1 Cedar Grove Coke

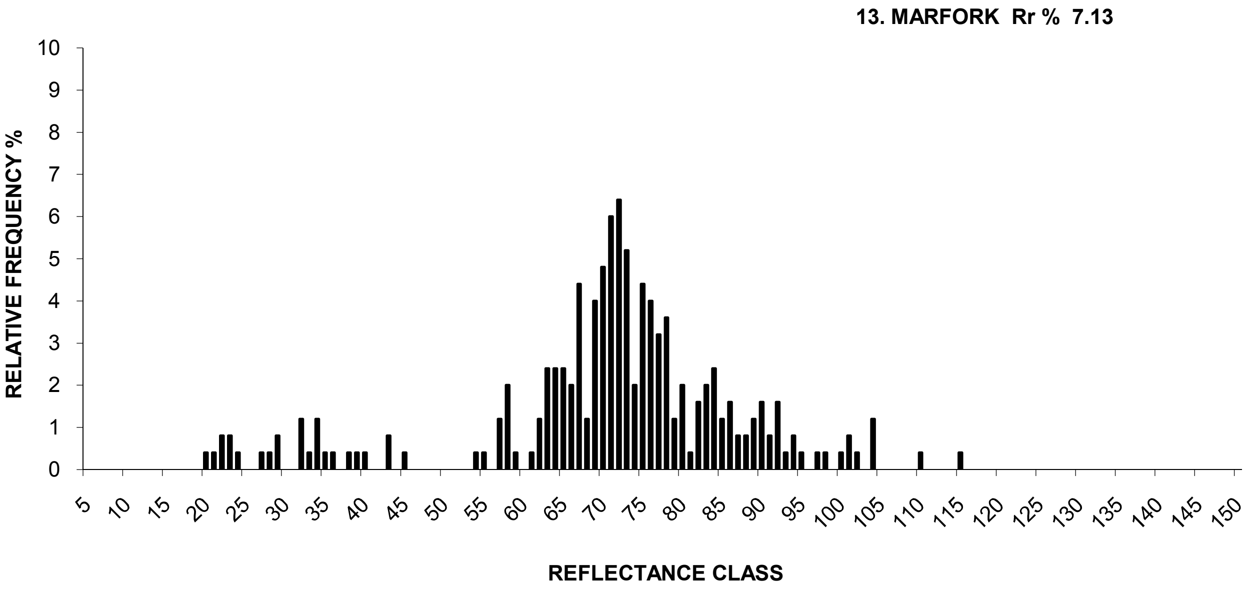

Figure 13 Appendix 1 Marfork Eagle Coke

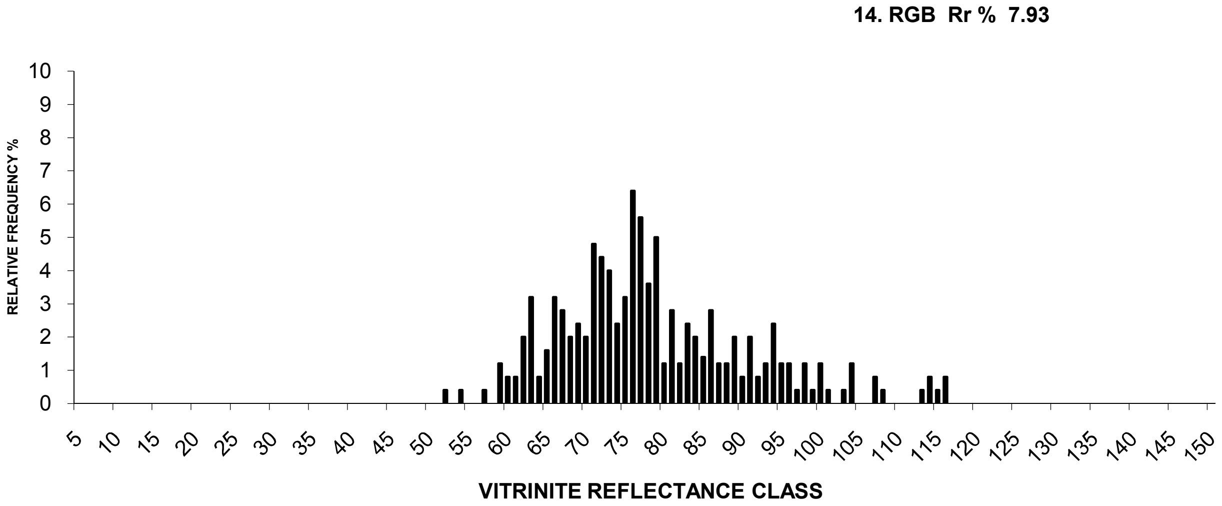

Figure 14 Appendix 1 Riverside Goonyela Coke

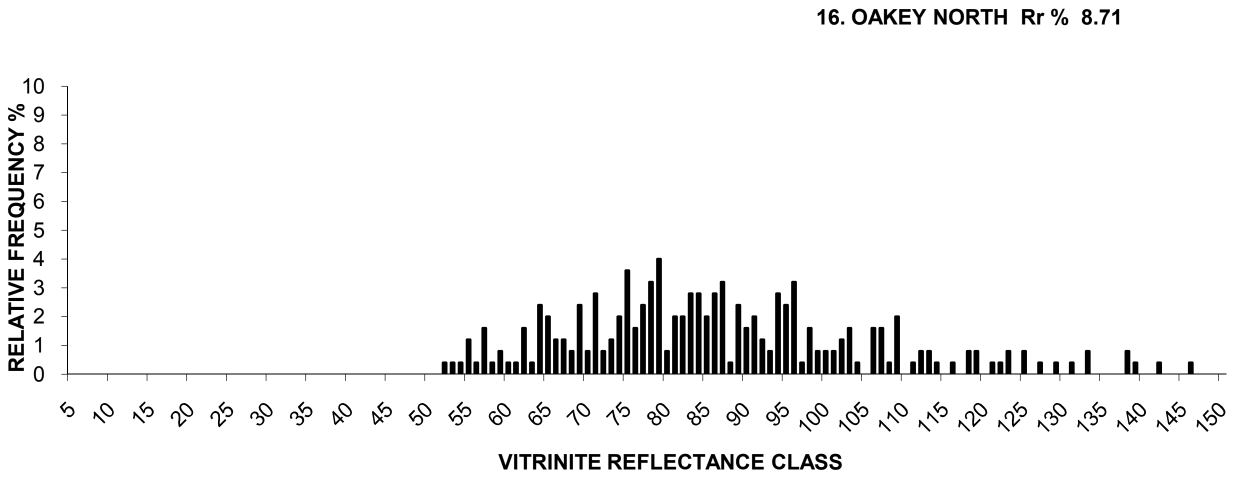

Figure 15 Appendix 1 Oaky North Coke

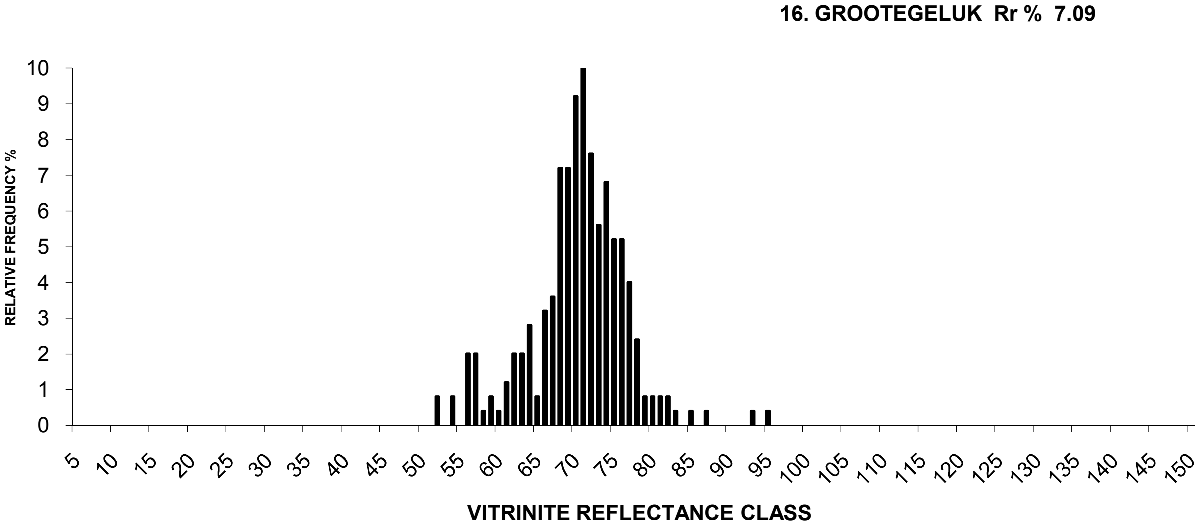

Figure 16 Appendix 1 Grootegeluk Coke

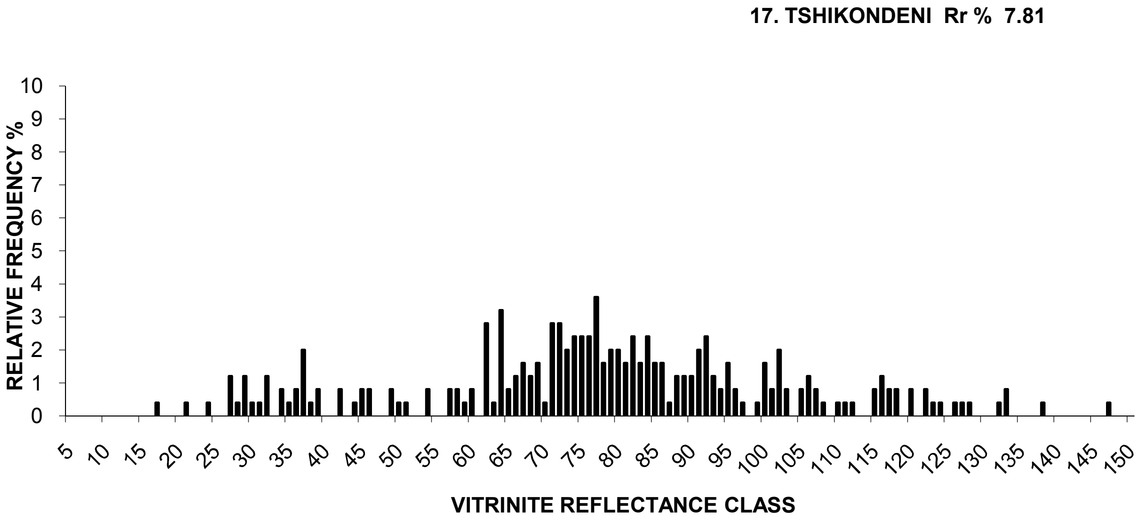

Figure 17 Appendix 1 Tshikondeni Coke

Table 17 Single Coke Component, Physical Properties Analyses

SAMPLE CODES	1 TWIN ROCK	2 KNOX CREEK	3 ARCH EXPORT	4 SHOAL CREEK	5 AMFIRE	6 KEPLER	7 OAK GROVE
Cold Strength							
$M40/_{30}$	80.3	55.3	45.0	79.2	79.2	79.8	78.0
$M30/_{30}$	89.9	75.4	68.7	89.1	89.4	89.7	88.9
$M10/_{30}$	5.8	11.0	9.3	6.5	6.9	5.9	5.9
$I40_{30}$	59.2	27.0	13.8	54.7	58.3	58.1	55.3
$I30/_{30}$	73.8	47.9	37.0	70.2	74.5	74.9	72.0
$I20/_{30}$	79.6	64.8	62.4	76.1	79.4	80.3	79.0
$I10/_{30}$	19.1	29.3	25.5	22.0	19.1	18.1	19.1
Theoritcal Coke Yield %	77.8	68.7	66.8	75.9	80.6	82.4	81.1
Coke Yield %	79.1	73.2	69.2	76.9	77.1	74.7	75.4
H_2O	1.0	3.2	4.4	1.1	3.2	1.0	1.2
Hot Sterngth							
CRI	20.5	43.0	29.2	21.9	47.7	25.4	17.3
CSR	67.5	28.8	55.7	63.5	17.0	65.4	76.6
Chemical							
% Na2O	0.18	0.23	0.32	0.31	0.19	0.22	0.24
% MgO	0.1	0.1	0.1	0.1	0.1	0.1	0.1
% Al2O3	3.4	3.8	2.6	4.1	3.0	2.1	3.7
% S1O2	5.2	6.9	3.5	5.8	3.8	2.3	5.4
% P	0.018	0.020	0.010	0.039	0.027	0.013	0.038
% K2O	0.28	0.23	0.25	0.30	0.23	0.20	0.25
% CaO	0.3	1.2	0.2	0.4	0.4	0.1	0.3
% TiO2	0.17	0.23	0.16	0.18	0.15	0.10	0.23
% Mn	0.00	0.01	0.01	0.01	0.01	0.01	0.01
% Fe	0.8	0.6	0.7	0.8	0.8	0.3	0.3
Proximate Analysis							
% Ash	11.2	14.2	8.4	13.0	10.0	6.0	10.9
% S	0.8	0.57	0.62	0.73	1.05	0.65	0.52
% Vol	0.70	0.8	0.60	0.80	0.7	0.90	1.10
Fixed Carbon	88.1	85	90	86.2	89.3	93.1	88
International (ASTM)							
Stability Factor mm	57.0	29.1	24.5	53.7	57.7	53.6	56.7
Hardness Factor mm	64.1	54.1	56.5	58.9	62.9	61.7	64.9

Table 18 Single Coke Component, Physical Properties Analyses

SAMPLE CODES	8 BLUE CREEK 4	9 BLUE CREEK 7	10 PINNACLE	11 WELLS	12 CEDAR GROVE	13 MARFORK
Cold Strength						
M40/$_{30}$	75.8	79.0	69.4	62.4	62.5	63.6
M30/$_{30}$	88.1	90.5	86.3	80.5	83.6	51.5
M10/$_{30}$	6.3	5.5	8.5	8.6	8.4	8.1
I40$_{30}$	53.8	53.3	41.4	33.6	34.3	36.2
I30/$_{30}$	70.7	73.6	65.3	56.7	58.1	58.0
I20/$_{30}$	78.1	78.8	73.8	70.7	70.6	71.3
I10/$_{30}$	20.1	19.5	24.7	24.7	25.3	24.2
Theoritcal Coke Yield %	72.5	80.3	84.9	65.9	68.3	68.2
Coke Yield %	77.6	78.3	81.6	75.1	82.2	81.2
H_2O	1.2	1.2	0.8	1.0	1.6	2.4
Hot Sterngth						
CRI	21.7	24.1	33.1	23.5	24.0	21.6
CSR	66.5	70.2	46.0	56.8	60.1	57.8
Chemical						
% Na2O	0.35	0.26	0.31	0.18	0.31	0.30
% MgO	0.2	0.1	0.1	0.1	0.1	0.1
% Al2O3	3.4	3.3	3.1	2.7	2.7	2.3
% S1O2	5.8	5.0	3.8	4.0	3.5	2.8
% P	0.050	0.030	0.014	0.009	0.008	0.008
% K2O	0.33	0.26	0.17	0.21	0.22	0.28
% CaO	0.4	0.3	0.3	0.2	0.1	0.1
% TiO2	0.19	0.19	0.17	0.14	0.13	0.12
% Mn	0.01	0.00	0.01	0.01	0.01	0.01
% Fe	0.5	0.5	0.7	0.5	0.6	0.5
Proximate Analysis						
% Ash	11.6	10.4	9.5	8.7	8.4	7.4
% S	0.65	0.61	0.7	0.67	0.77	0.77
% Vol	1.00	1.10	1.10	1.10	0.90	1.20
Fixed Carbon	87.4	88.5	91.3	90.2	90.7	91.4
International (ASTM)						
Stability Factor mm	54.7	57.9	45.6	35.8	36.6	39.9
Hardness Factor mm	63.6	64.0	54.6	57.0	55.2	59.7

Table 19 Single Coke Component, Physical Properties Analyses

SAMPLE CODES	14 RGB	15 OAKEY NORTH	16 GG	17 TSK
Cold Strength				
M40/$_{30}$	78.0	81.7	28.0	74.9
M30/$_{30}$	88.0	90.7	57.2	86.6
M10/$_{30}$	8.3	5.3	9.7	7.4
I40$_{30}$	52.2	60.9	6.5	52.0
I30/$_{30}$	69.5	73.5	26.3	69.6
I20/$_{30}$	74.7	78.8	63.8	76.8
I10/$_{30}$	24.2	19.7	19.6	21.3
Theoritcal Coke Yield %			64.6	80.3
Coke Yield %	72.7	76.0	72.0	79.9
H_2O	2.2	1.3	1.6	2.8
Hot Sterngth				
CRI	25.8	16.1	44.2	20.8
CSR	61.9	72.2	31.7	66.2
Chemical				
% Na2O	0.03	0.20	0.20	0.38
% MgO	0.1	0.1	0.1	0.3
% Al2O3	4.1	4.1	3.3	3.9
% S1O2	8.4	5.0	10.3	8.9
% P	0.016	0.053	0.010	0.038
% K2O	0.11	0.15	0.16	0.25
% CaO	0.1	0.3	0.2	0.6
% TiO2	0.19	0.24	0.25	0.22
% Mn	0.01	0.01	0.01	0.01
% Fe	0.3	0.5	0.6	0.4
Proximate Analysis				
% Ash	13.5	11.0	15.5	15.8
% S	0.51	0.53	0.89	0.76
% Vol	1.5	1.20	1.60	0.9
Fixed Carbon	85.0	87.8	82.9	83.3
International (ASTM)				
Stability Factor mm	51.2	56.2	12.2	49.3
Hardness Factor mm	57.9	62.1	61.7	59.7

APPENDIX 2

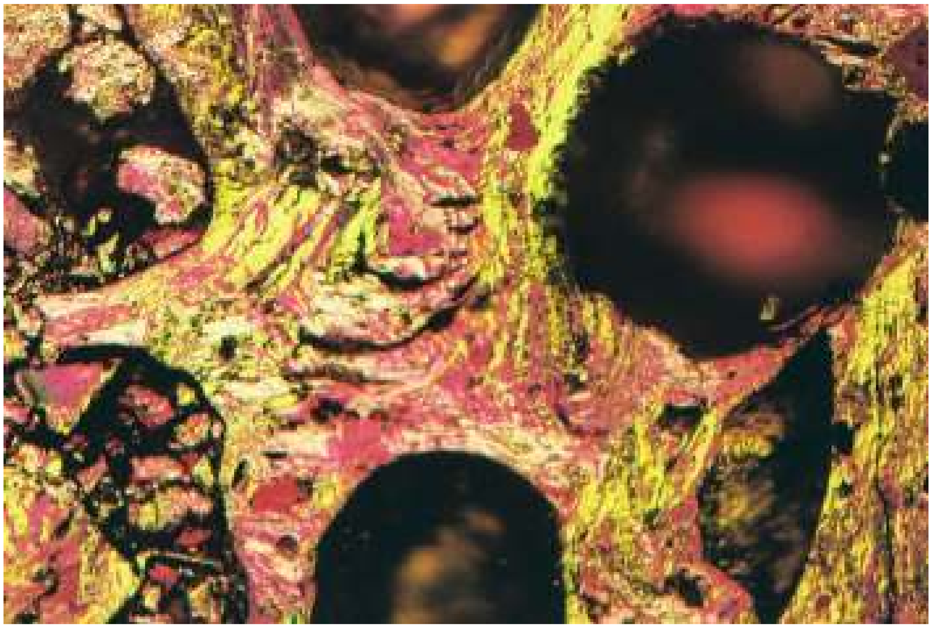
Figure 1 Appendix 2 Blue Creek No. 7 Coke - Lenticular and ribbon form binder phases

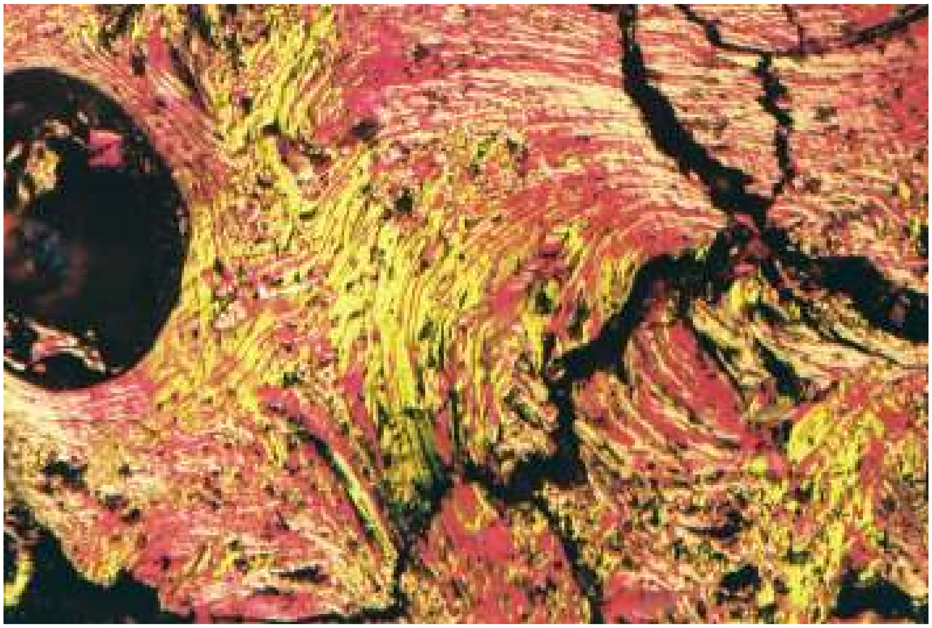
Figure 2 Appendix 2 Pinnacle Coke - Anisotropic fine to medium ribbon textures

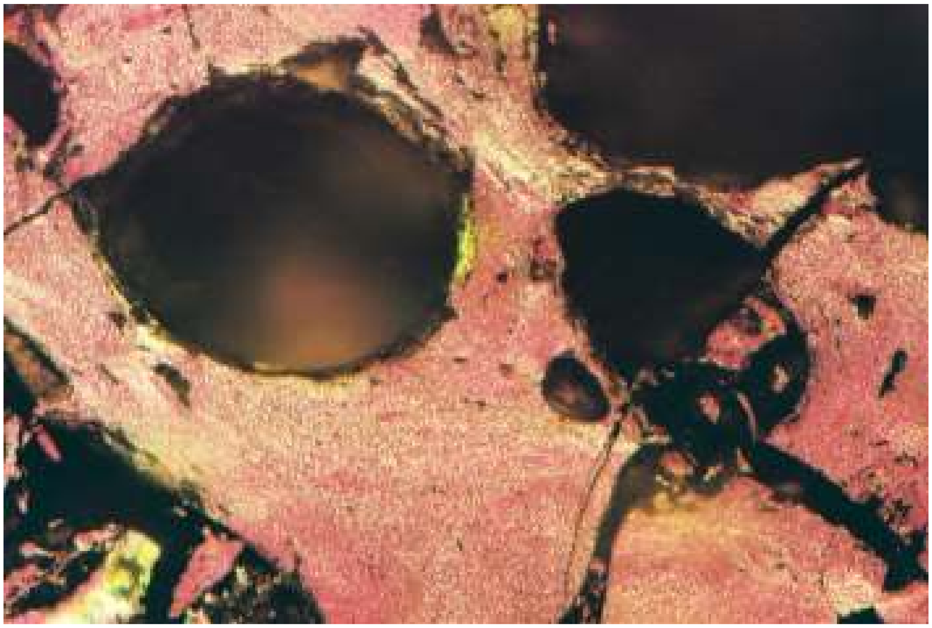

Figure 3 Appendix 2 Wells Coke - Circular (granular) anisotropic textures

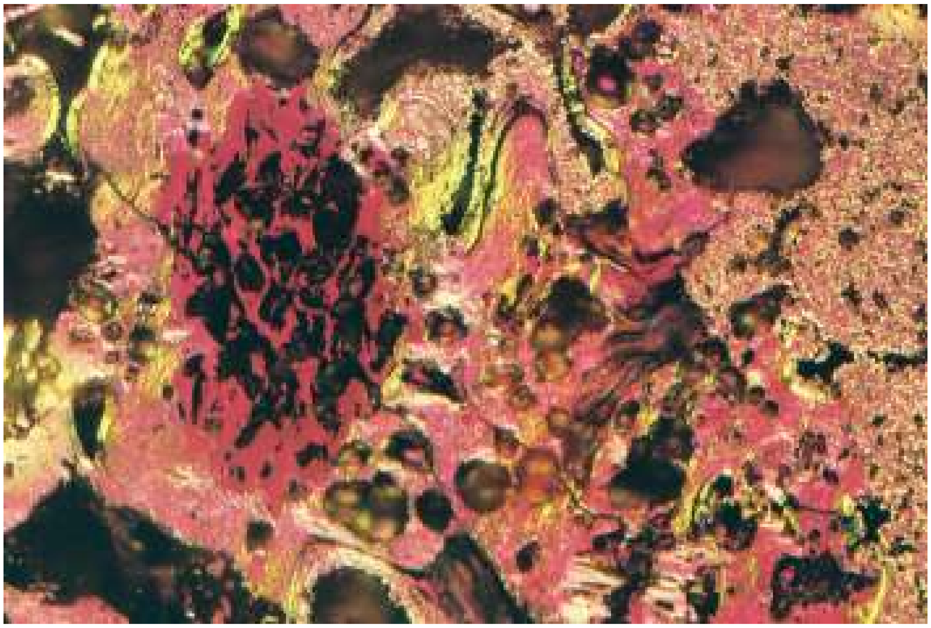

Figure 4 Appendix 2 Wells Coke - Binder /filler phases with relatively small gas vesicles

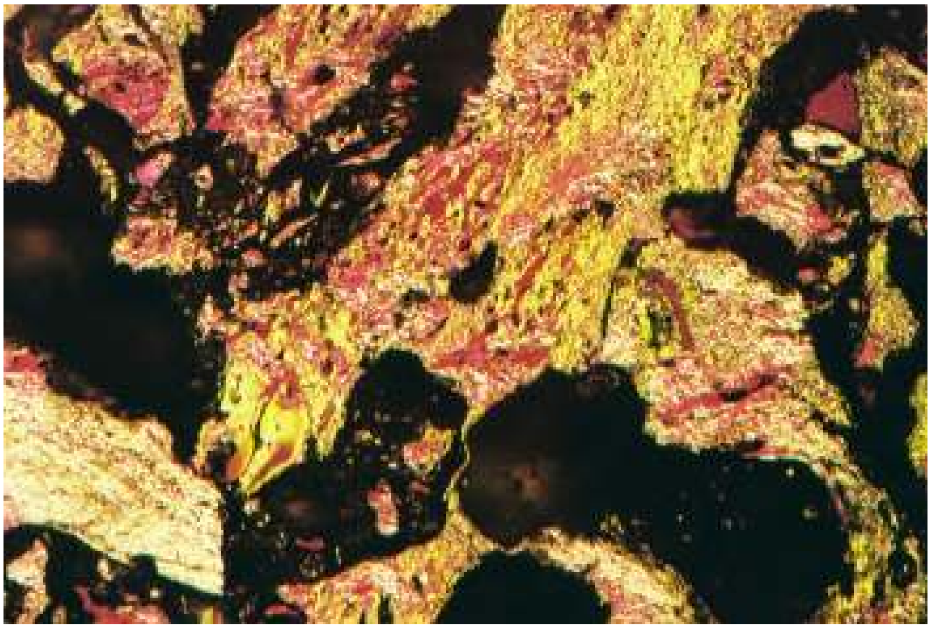

Figure 5 Appendix 2 Oaky North Coke - Development of lenticular anisotropic textures in coke walls.

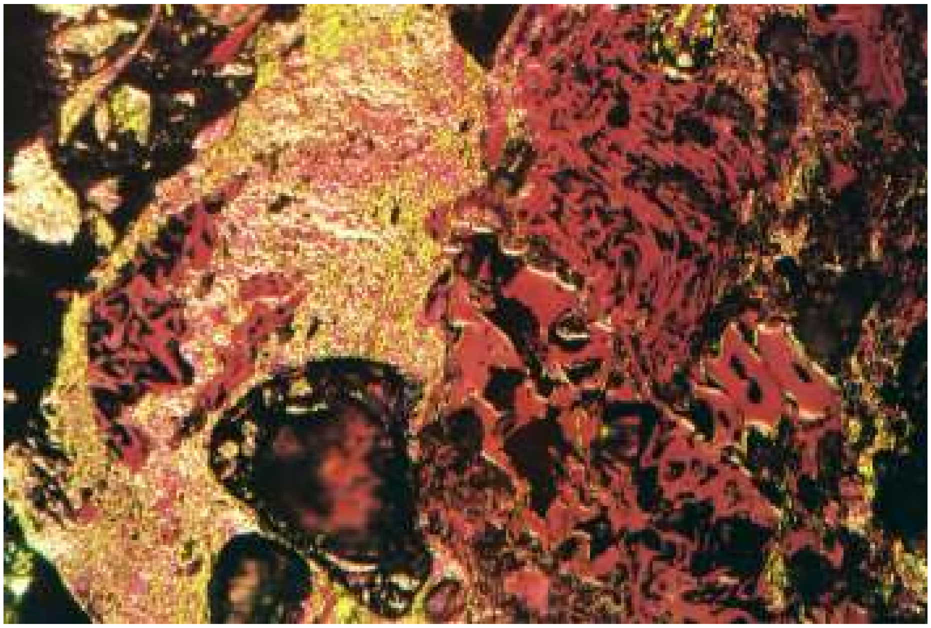

Figure 6 Appendix 2 Oaky North Coke - Bonding between the binder phase (left) with coarse organic filler (right).

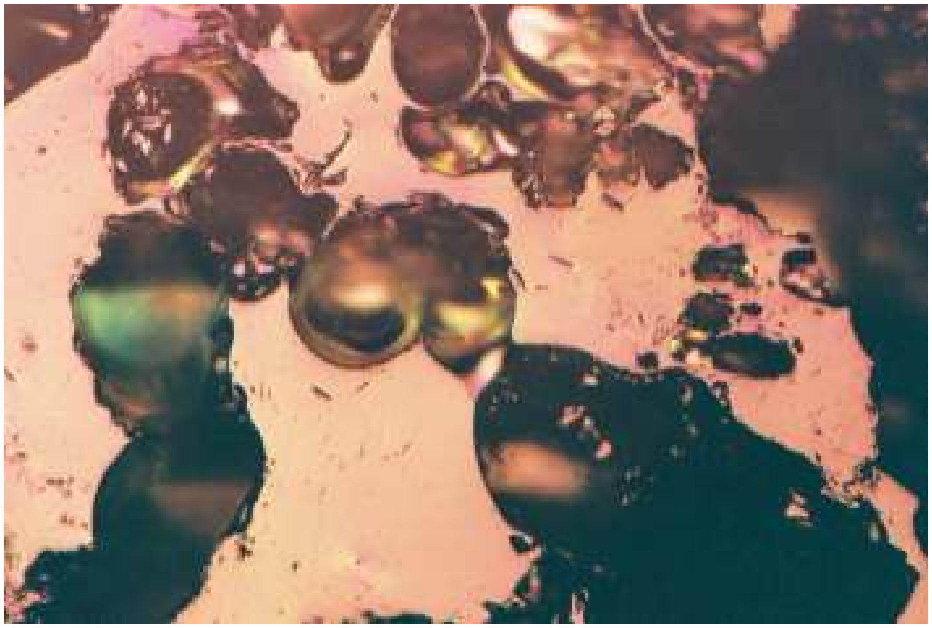

Figure 7 Appendix 2 Grootegeluk Coke - Thick-walled isotropic binder phase carbon

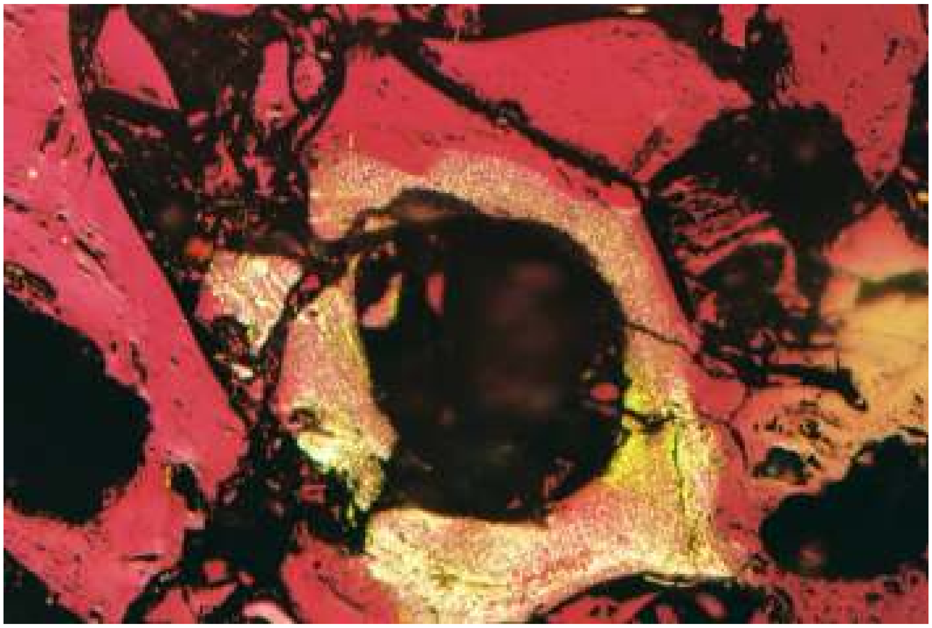

Figure 8 Appendix 2 Grootegeluk Coke - Development of anisotropic fine circular domains

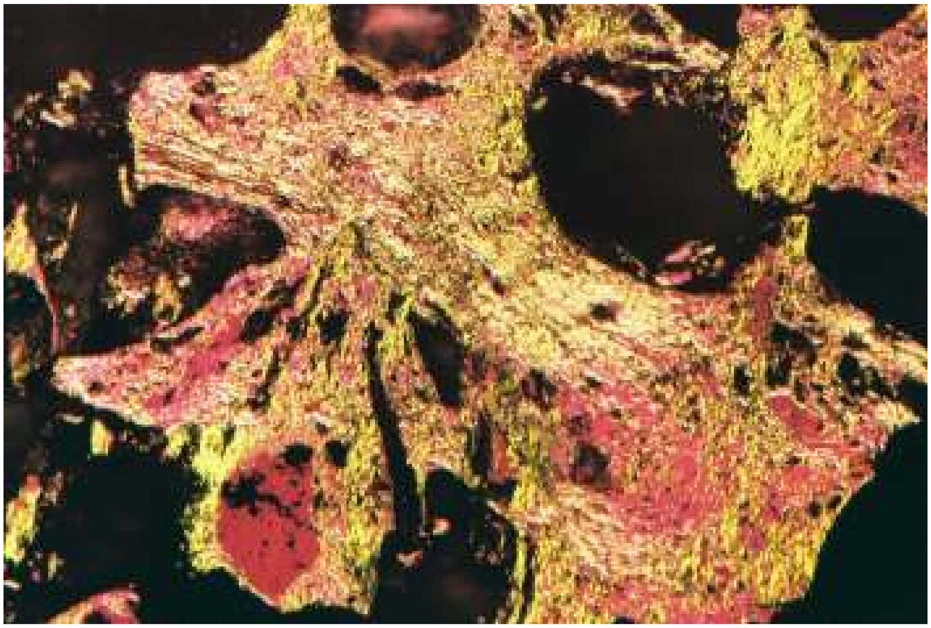

Figure 9 Appendix 2 Tshikondeni Coke - Lenticular anisotropic binder phase