The Technical Evaluation of Non-coking Coals in the Production of Semi-coke

MSc (50/50) RESEARCH REPORT

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Submitted to

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July, 2018

Declaration

I declare that this research report is my own, unaided work. It is being submitted in fulfillment for the degree of Master of Science in Engineering (Chemical Engineering) to the University of the Witwatersrand, Johannesburg. It has not been submitted previously for any degree or examination to any other University.

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Abstract

Grootegeluk Coal Mine produces a metallurgical non-coking coal that is used in the production of semi-coke. Semi-coke is a new product that is used as a reductant in ferrochrome furnaces. The Exxaro semi-coke is of a high quality and is able to substitute the locally produced market coke due to its comparable (and better) strength and reactivity indexes.

This research was started to better understand the Exxaro semi-coke and the competitive advantage that comes from the single coal source in the production of semi-coke. In addition, it is important to understand if there are any other non-coking coals available in the Witbank and Highveld coalfields that can produce a similar product and replace Exxaro as a market leader.

Coals were selected from the Waterberg, Witbank and Highveld coalfields. These coals were then subjected to proximate testing and full petrographic analysis before being "charred" mimicking actual production parameters. The "charred" coals were then evaluated using petrographic analysis to better understand their inherent structures and their role in CSR and CRI.

It was found that the vitrinite reflectance of the selected coals were in a very close range of 0.67 - 0.69. It could be found that a suitable semi-coke with comparable CSR and CRI indexes could be produced from 6 of the 8 samples sourced from the Waterberg, Witbank and Highveld coalfields. However, the requirement for a substantial low phosphorus coal source will remain a barrier to entry for other potential producers of semi-coke as only minimal amounts remain.

In addition, it could be seen that semi-coke has a higher CSR than market coke due to the formation of anisotropic structures as compared to locally produced market coke that is predominantly isotropic. This ensures superior performance in the furnace

It is recommended that further work be completed to better understand the reasons for anisotropic structures in coals sourced from Exxaro. Further investigation should also be considered in utilizing coals of varying ranks in similar testing in the production of semi-coke.

Acknowledgements

A sincere acknowledgment goes to Exxaro Resources for providing the financial assistance to complete this research as well as to all my amazing colleagues for their genuine support and concern.

My heartfelt thanks also goes to the following special people:

- Professor Rosemary Falcon – thank you for your guidance and for being such an amazing inspiration to the coal community at large. It is an honour to have been your student.
- Samantha Maharajh – thank you for all your organising, planning and for entertaining all my millions of questions. You made it all appear effortless.
- My Parents – "Before a child believes in themselves, there was always a parent who believed first". Thank you for your unconditional support and love always.

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Nomenclature

Ash	This is the material that remains after combustion and is the total of the non-combustible minerals contained within the coal. Ash originates from several sources including the minerals contained, ingrained or infiltrated in the plant matter.
Semi-coke	This is a reductant produced exclusively by Exxaro in South Africa for use in the ferrochrome markets. It is produced from a single source of coal and is characterized by high CSR and CRI in a furnace.
Reductants	A reductant is a carbonaceous material used in a furnace environment. It is also defined as a substance capable of bringing about the reduction of another substance as it itself is oxidized.
Porosity	This is the state or quality of being porous. It is the measure of the void spaces between particles.
Coal	Coal is a complex heterogeneous sedimentary organic rock, made up of fossilized plant matter and inorganic matter.
Calorific Value	The amount of heat that is released when coal is combusted.
Char	This is a carbon enriched product produced from a high temperature heating process that drives off the volatile matter in the coal. This process occurs in the absence of oxygen to prevent combustion of the coal feed.
CRI	CRI is the abbreviation for the Coke Reactivity Index. CRI measures the reactivity of the reductant in a high temperature CO/CO_2 environment. The weight loss of the reductant equals the Coke Reactivity Index.
CSR	CSR is the abbreviation for Coke Strength after Reaction. CSR measures the potential of the reductant to break into a smaller size under a high temperature CO/CO_2 environment that exists. It is also an indication of the mechanical strength of the reductant.

Free Swelling Index	A coal property that describes the degree of swelling that takes place when the coal is heated. These coals are used in the production of coke.
Fixed Carbon	The fixed carbon content of coal provides the energy and metallurgical ability that coal is valued for. The higher the fixed carbon, the higher the calorific value. Levels of carbon increase with increasing coal rank.
Inertinite	This is a microscopic constituent or maceral found in coal. Inertinite is derived from woody tissue that has been altered by fire or biochemical charring. The major inertinite components are fusinite and semi-fusinite.
Liptinite	This is a microscopic constituent or maceral found in coal. Liptinite is derived from the waxy and resinous parts of the plant. It mainly consist of sporinite, resinite and cutinite derived respectively from plant spores, resins and cuticles.
Macerals	These are the basic microscopically observable components of coal. Macerals are generally divided into 3 groups namely vitrinite, liptinite and inertinite and reveal the depositional histories and botanical precursors for coal.
Moisture	A high moisture content is related to a low calorific value in coal.
Metallurgical Coal	Coals that have suitable qualities and properties suitable for metallurgical processes.
Phosphorus	This is a coal constituent that is calculated using the P_2O_5 content of the ash content in the coal. It is very problematic for metallurgical applications for coal as it reduces the ductility of steel and causes cracking at low temperatures.
Roga Index	This is a measure used to describe the mechanical strength of coke.
Sulphur	Sulphur can be present in 3 different forms in coal (pyrite, organic and sulfate). The presence of sulphur is undesirable in the use of coal as a fuel source. Oxidation of sulphur can lead to air pollution

	and acidification. In metallurgical applications, it causes cracking when steel is forged at high temperatures. Sulphur content is not related to coal rank.
Vitrinite	This is a microscopic constituent or maceral found in coal. The vitrinite group is derived from the coalified woody tissue and is found in very high proportions in North American coals.
Vitrinite Reflectance	This is the measured intensity of a proportion of polarized light reflected from a randomly selected flat, well-polished surface of vitrinite. It is an established method to determine the rank or degree of maturation of coal and is commonly referred to %RoV.

1. INTRODUCTION

Exxaro is one of the largest South African based diversified resources groups, with interests in the coal, titanium dioxide, ferrous and energy markets. Exxaro is the second-largest coal producer in South Africa with current production of almost 40 million tonnes per annum (Mtpa), and is listed on the JSE Limited, where it is a constituent of both the Top 40 and Socially Responsible Investment (SRI) indices.

Although Exxaro is still relatively young, the pedigree and wealth of skills stretch back over decades as a company rooted in South Africa and respected among its peers for its innovation, ethics and integrity. The Reductants Plant is the result of Exxaro's focus on downstream beneficiation opportunities in the coal market, specifically in the production of reductants for the ferroalloys industry.

Exxaro constructed the Reductants Plant in 2008. It is situated alongside the Grootegeluk Coal Mine in Lephalale, Limpopo Province. The operation has four retorts and is a producer of high quality semi-coke. Semi-coke is used extensively as a reductant in the ferroalloy industry predominantly in ferrochrome smelting. It was originally used as a char product and then further developed into a semi-coke niche market as more consumer testing showed that semi-coke can be used to substitute traditional market coke.

Semi-coke is produced from the metallurgical seams which are also commonly referred to as the non-coking coal seams, (predominantly Bench 9 and 11) from the Grootegeluk Mine. The strategic positioning of the Reductants Plant was to "match" the coal source. It is suspected that the single coal source with superior metallurgical properties is a large contributor to the successful production of the semi-coke.

The Exxaro semi-coke is the first of its kind in South Africa with properties very comparable to traditional South African market coke. The Coke Strength after Reaction (CSR) and the Coke Reactivity Index (CRI) are superior to locally produced market coke and these parameters have convinced the Ferroalloy producers to use the semi-coke as a market coke substitute.

Whilst any reference to CSR and CRI has always been associated to Blast Furnace steel-making operations, the ferrochrome smelters are now fully aware of its importance in smelting applications.

In South Africa, there are two types of cokes produced i.e. metallurgical and market coke. The metallurgical coke is used as part of the iron making process in a blast furnace. Given the size of a blast furnace, metallurgical coke has a high CSR value to support the burden in the blast furnace. Market coke on the other hand, is used in the much smaller ferroalloy furnaces. Market coke has a much lower CSR than metallurgical coke ensuring that the furnace reaction runs to completion.

Exxaro semi-coke has been specifically produced to easily substitute market coke for use in ferroalloy application and have superior properties that add stability to the furnace operation.

As semi-coke becomes more widely known to the marketplace and more sought after as an alternative to market coke, it is important to understand its properties and the reason for its superior performance. Currently, it is believed that a single coal source is the key contributor to its success. But there has been very little academic work conducted either on the feed coal or the product, semi-coke, to prove this. For this reason, research in these fields is expected to add meaningfully to the body of knowledge. In addition, such research would be significant as it evaluates non-coking coal properties to determine whether other

coals in other regions can provide similar advantages in the production of semi-coke.

1.1. Research Objectives(s):

The key objectives of this research are the following:

a) To evaluate Exxaro non-coking coals in the production of semi-coke with specific relevance to CSR and CRI parameters as required in ferroalloy application.
b) To determine whether other coal sources can produce a semi-coke similar to Exxaro semi-coke.
c) To establish the reasons for, and to better understand, the superior performance of the non-coking coals in semi-coke production relative to market coke. This would include full characterisation of both coals, the resultant semi-cokes and a controlled sample of the market coke.

1.2 Hypothesis

Semi-coke can only be produced from the Grootegeluk Mine coal source. The competitive advantage is in the single coal source with superior metallurgical properties that cannot be replicated in the Witbank or Highveld coalfields.

1.3 Key Questions to be answered

This research study will answer the following key questions:

1. What are the key properties of the Grootegeluk Mine coal that contribute to the desired CSR / CRI?
2. How do the CSR / CRI value of high ash coals (benches) from the Grootegeluk Mine compare with the semi-coke produced from the Grootegeluk Mine Bench 9 and 11?

3. How do coals in the Witbank and Highveld coalfields compare to the Grootegeluk Mine coal in the production of semi-coke in consideration of CSR / CRI?
4. If different, what are the different properties and performance characteristics between them?
5. How will strategic advantage be determined from information obtained from this semi-coke investigation?

2. LITERATURE REVIEW

2.1 The role of carbon reductants in the ferrochrome process

According to the Handbook of Ferroalloys (2013), nearly 85% - 90% of all ferroalloys are used in steelmaking and steel and iron foundries. By definition (Gasik, 2013), ferroalloys are the alloys of two or more metals, of which iron is one. A leading element is the main component (e.g. chrome would be the leading element in the production of ferrochrome). The main task of the ferroalloys industry is the recovery of needed metals from natural minerals by the process of reduction (e.g. ferrochrome from chromium ore).

South Africa is and has been a leading player in the international ferroalloys industry. Historical factors that have contributed to this dominant position include an abundance of natural resources and relatively low cost electricity. However a number of developments have changed this position. This includes labour disruptions, the limited availability of electricity during certain periods and the drastic increases in electricity prices that have forced producers to consider their operating circumstances. (Pan, 2015 – INFACON 2014). The industry has since seen much consolidation in response to worldwide commodity pricing.

However, the following ferroalloys are produced in South Africa:

- Ferrochrome
- Ferromanganese
- Ferrosillicon
- Ferrovanadium

These metal ores are predominantly oxides and hence their carbothermic reductions are generally the same. However the reaction

temperature, furnace refractories, reductant consumptions, and reaction times do differ.

In these carbothermal (reduction) processes, carbon is the main reductant of the oxygen in the metal oxides. Carbon (in its various forms) can reduce practically all elements from their oxides at high temperatures. In a traditional submerged arc furnace such as is used in the production of ferrochrome, electrodes produce the initial high temperatures. Carbon reduces the oxides followed by formation of a liquid slag and metallic phase in the progress of reduction. The smelting process consists of many steps at varying temperature ranges resulting in molten, reduction and gas phases. (Gasik, 2013).

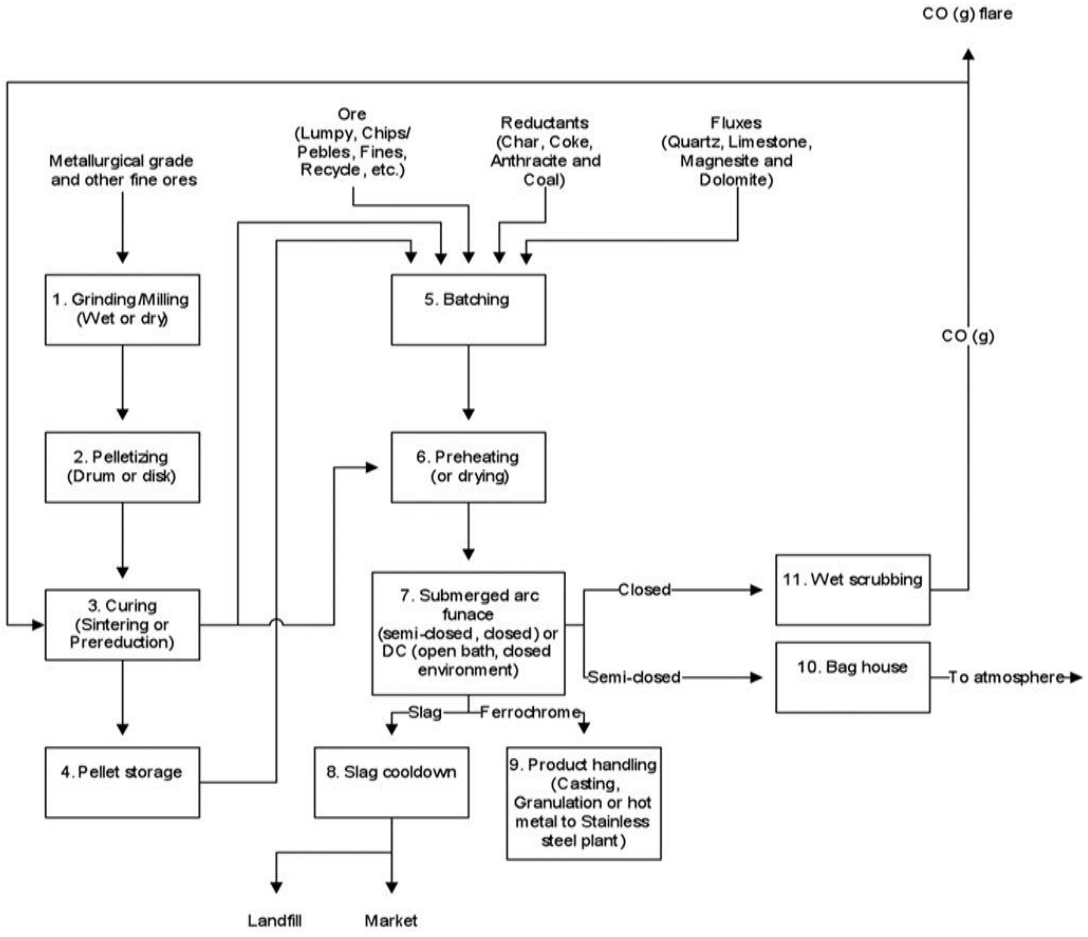

Figure 1 – General Ferrochrome process (Exxaro Research, 2015)

It is obvious that the reductant or reductant blend plays a critical role in this process. In ferrochrome production, "reductants are used to reduce the reducible components in the chromite ore to the metallic or carbide states, which form the alloy" (Gasik, 2013). Reductants are characterized by their reactivity and their ability to provide permeable support for the burden in the furnace. A variety of reductants can be used in the production of ferrochrome and the selected reductants for a particular smelter would depend on a variety of factors including technology, availability and cost-effectiveness" (Gasik, 2013). Market coke is deemed a particularly suitable reductant in South Africa as it contributes to the formation of the coke bed and has acceptable reactivity. Other commonly used reductants in the South African ferrochrome industry include anthracite, coal and char.

Coke

In South Africa, Arcelor Mittal South Africa (AMSA) produces two distinct cokes i.e. *metallurgical coke* and *market coke*. *Metallurgical coke* is produced by destructive distillation of predominantly hard coking coals and a blend of other coals of a specific rank at temperatures of up to 1100^{0}C using coke batteries / ovens. The properties of caking ability, reactivity and strength after reaction (burden support) are considered extremely important as metallurgical coke is used to maintain the process of iron production in the blast furnace. (Kruger, 2013 and Diez et al., 2002)

Ferroalloy applications cannot use metallurgical coke in their furnaces as these furnaces are much smaller than blast furnaces. In addition, the reactivity is too low and the strength is much too high thus not allowing the furnace reactions to go to completion. As a result, large amounts of carbon are left in the slag. To this end, AMSA produces a *market coke* from a blend of various less specialised and less expensive coals that have a higher reactivity and a much lower strength. (Kruger, 2013).

Various relationships affect the key properties of coke, namely, coke strength after reaction (CSR) and the coke reactivity index (CRI) (Diez, 2002). These measures are commonly used in measuring metallurgical coke quality in blast furnaces as they measure coke resistance to degradation.

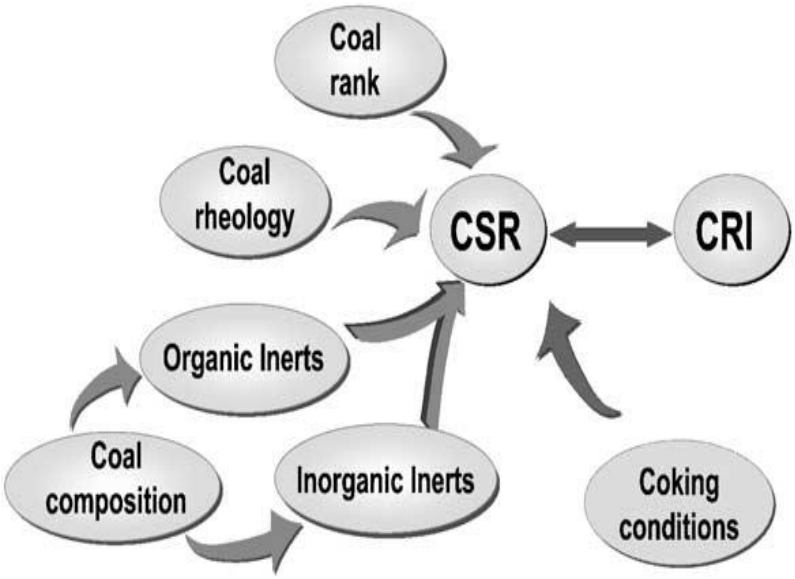

Figure 2 - Main factors influencing CSR - Diez (2002)

Figure 2 presents the various factors that influence CSR and CRI, including the nature and origin of the source coals and the conditions in which the coke is produced. In recent years such factors have included the rank and chemistry of the parent coals which affect the textures of coke together with porosity and ash chemistry (Diez, 2002).

Char

Char in South Africa is produced via the process of pyrolysis. This is the first stage of combustion when particles are devolatilized at 300 - 400^{0}C in the absence of oxygen resulting in a carbon rich solid residue. Char in South Africa

is produced from non-coking coals which, upon heating, do not soften and are instead converted to char. The properties of the char are influenced directly by the properties of the parent coal and the processing temperature (Jordan, 2006).

The first char plant was commissioned by Exxaro in 2008 and this initially produced a char product for the ferroalloy industry. However, after understanding the influence and effect of the parent coal used in the process, the product was re-branded as *semi-coke*. The process parameters in the plant were also adjusted to increase retention time without compromising the structure or the porosity (Jordan, *pers com).*

After a number of trials, the producers of ferrochrome confirmed that Coke Strength after Reaction (CSR) and Coke Reactivity Index (CRI) are important measures (amongst others) in determining suitable reductants and reductant blends for their industry (van der Merwe, *pers.com*; Terblanche, *pers com*.). Namely, a reductant for the ferrochrome industry needs to be strong enough to withstand the burden of the submerged arc furnace and reactive enough to ensure that the carbon is consumed in the gasification phase and therefore does report in significant quantities to the slag.

The Exxaro *semi-coke* is reported to add stability to ferrochrome furnaces due to its higher strength as compared to traditionally used *market coke*. In addition, the reported reactivity indicates that the *semi-coke* is rapidly consumed in the early gaseous reduction process as well as providing an ideal permeable medium for ferrochrome furnace performance.

The Exxaro semi-coke is produced from coals low in sulphur (S) and phosphorus (P) content. This is ideal as sulphur and phosphorus are contaminants in the production of stainless steel. Excess sulphur is known to affect the “toughness” of stainless steel and will lead to downstream problems in the manufacturing and rolling of final products. Phosphorus, when present in steel, renders it brittle

and prone to cracking. Given the effects of these components, it is imperative that ferroalloy reductants have low phosphorus and sulphur contents.

Table 1: Comparative Reductants (Kruger, 2012 and Exxaro Research, 2013)

	AMSA Market Coke	Exxaro Semi Coke	Xstrata Char
DFC %	83.1	80	76
CSR	27	45 – 50	22
CRI	45	40 – 45	52
Phos %	0.012	0.012	0.012
Sulphur %	0.97	0.65	0.70
Volatiles %	0.9	2.5	5
Ash %	16.0	17.0	19.0

Table 1 presents the properties of Exxaro's semi-coke relative to two other commercial reductants currently used in the ferroalloy industry. From this data, it would appear that Exxaro's semi-coke is at least equal, and in some instances superior, to these other products. However, as a new product in South Africa, there is little or no literature available yet on its empirical value in a ferroalloy furnace.

The fact that Exxaro's semi-coke could potentially substitute market coke in the ferrochrome industry has far reaching commercial implications for semi-coke. For this reason, it is important to establish the reasons for the special qualities and characteristics of semi-coke and whether such a product can be produced from other coals. This research seeks to provide answers to such questions and, once achieved, will also determine the marketing strategy for this product.

2.2 Coal Formation and Coalfields

Coal qualities in the coalfields of the world vary considerably. Falcon (1988) showed that nearly 250 million years ago, the earth looked very different. Gondwana (in the southern hemisphere) and Laurasia (in the northern hemisphere) were two supercontinents separated by the Tethys Sea. These supercontinents experienced different climates, vegetation, geological settings, sedimentary environments and ultimately different levels of depths and pressures which impacted on the levels of maturity or rank of the coals. Such differences in the origin and formation of the original peat swamps lead to very different coals being formed in each of the hemispheres.

Over time, the build-up of silt and other sediments, together with movements in the earth's crust - known as tectonic movements, buried the swamps and peat deposits in Laurasia to great depths. With burial, the plant material was subjected to high temperatures and pressures leading to higher ranks (Figure 3). This caused physical and chemical changes in the vegetation, transforming it from peat into different levels ranks of coal. In Gondwanaland, and particularly in Southern Africa, coals remained for the most part at shallow depths but these were exposed to volcanic intrusions during the split up of Gondwanaland. As a result, when adjacent to hot lava flows passing through the coal seams, such coals were heated and the coals increased in rank in such localised areas.

A further difference of relevance to coal qualities is the nature of the organic composition of coal. The coals of the Laurasia formed from vegetation accumulating in hot steamy equatorial conditions and in wide expansive shallow water-logged swamps. In such conditions the bulk of the vegetational material (woody tree trunks and branches), gave rise to the organic maceral component known as vitrinite. This component retained much of its volatile material and thus, on heating, it is known to devolatilise rapidly, soften, swell, become porous

and under certain conditions, combustion rapidly (in oxygen) or form coke (in reducing conditions).

On the other hand, coals in Gondwanaland formed in cold to cool temperature conditions following a major ice age. Vegetational material accumulated in alternating long cold winters and short warm summers, often in dry conditions. Flooding, when snows or glaciers melted, would also bring down sandy or silty clay-rich sediments and re-worked organic material from the hinterland. This resulted in the formation of different organic components in the Gondwana coals relative to Laurasia. This included predominantly relatively inert or semi-inert organic components (inertinite macerals), formed in cold to cool dry conditions mixed with layers of reactive components, all of which had bands of sediment (clays or quartz) included in the seams to varying levels of concentration (Falcon, 1988). It is the latter forms of coal that are most prevalent in the South African coal fields and which need to be examined in the context of the reductants to be examined in this Research Report.

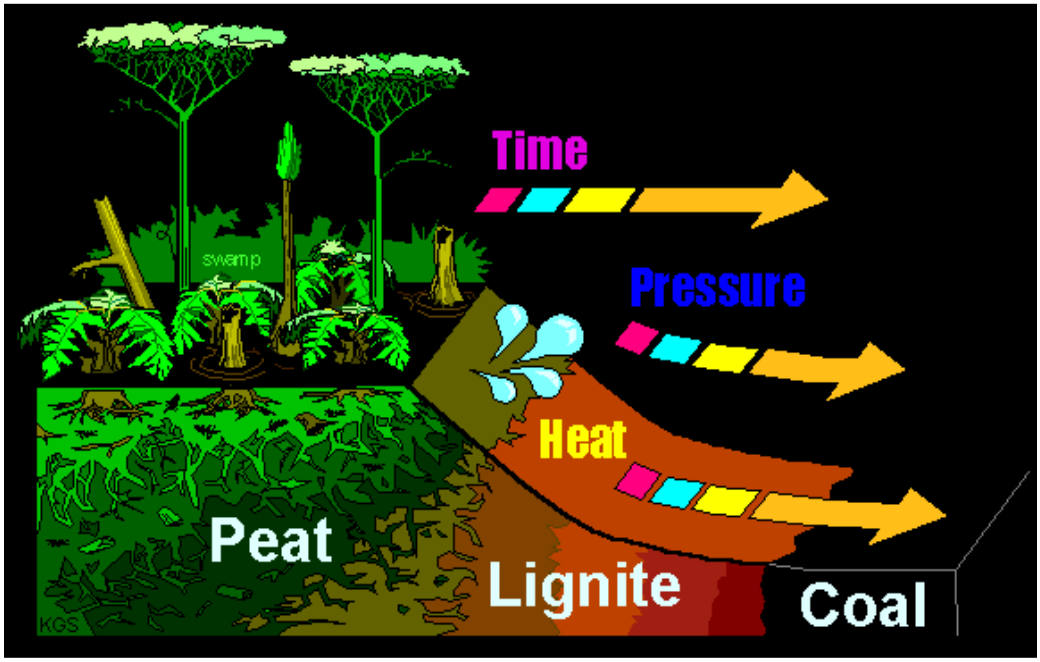

Figure 3 – Formation of Coal (adapted from Falcon, 2013)

The above facts require coal or coke, coke, char and semi-coke consumers to fundamentally understand the "biology" of the coals required in their processes. Such understanding would ensure that the correct coals or resulting carbon reductants would be selected for the right markets and thereby provide the correct applications. Falcon (1989) went on to explain that it is entirely possible to have two coals of similar proximate and ultimate analysis that display entirely different combustion patterns. This is largely attributed to the maceral differences that strongly influence combustion or reduction. Everson et al. (2013) further agreed that this was relevant in predicting combustion and gasification behavior.

Coalfields in South Africa

In South Africa, the coal deposits are found in 19 different coalfields (Figure 4). The coals found in these different coalfields vary considerably in composition and display different characteristics reminiscent of their formation and the geological changes that occurred during that period (Falcon, 1988).

Jeffrey (2005) and a desktop study by Prevost (2009) described the coalfields in detail and tabulated their differences in terms of quantity, quality and commercial utilisation of the coal seams. For the purpose of this study, only coalfields that are currently being economically mined were considered. Thus, whilst there are many coal mines in South Africa, Jeffrey (2005) confirmed that 70% of total South African reserves can be found in the Waterberg, Highveld and Witbank coalfields.

Therefore, after applying these criteria, only coal samples from the Waterberg, Witbank and Highveld coalfields were considered for testing and comparison against the coals that produce the Exxaro semi-coke. The selected coalfields are summarised in brief below.

The Waterberg coalfield is relatively unexplored with the exception of the Exxaro Grootegeluk Coal Mine. The Grootegeluk Mine is a multi-product mine with coals ranging from high quality metallurgical coals to high ash, low quality coals that are supplied to Eskom for power generation. The selective mining of various qualities has resulted in bench heights ranging from four to twenty meters (Jeffrey, 2005).

Characteristically, the seams in the Waterberg are relatively unique in that they possess a thick layer of uppermost coal known as the coal zone (up to 100m) made up of finely alternating layers of vitrinite-rich coal and clay-rich layers. Beneath this lies three discreet coals seams separated by varying sediments ranging from sandstones to carbonaceous shales and siltstones (Fourie, 2009). The source of the semi-coke product currently under investigation is one of the discreet coal seams.

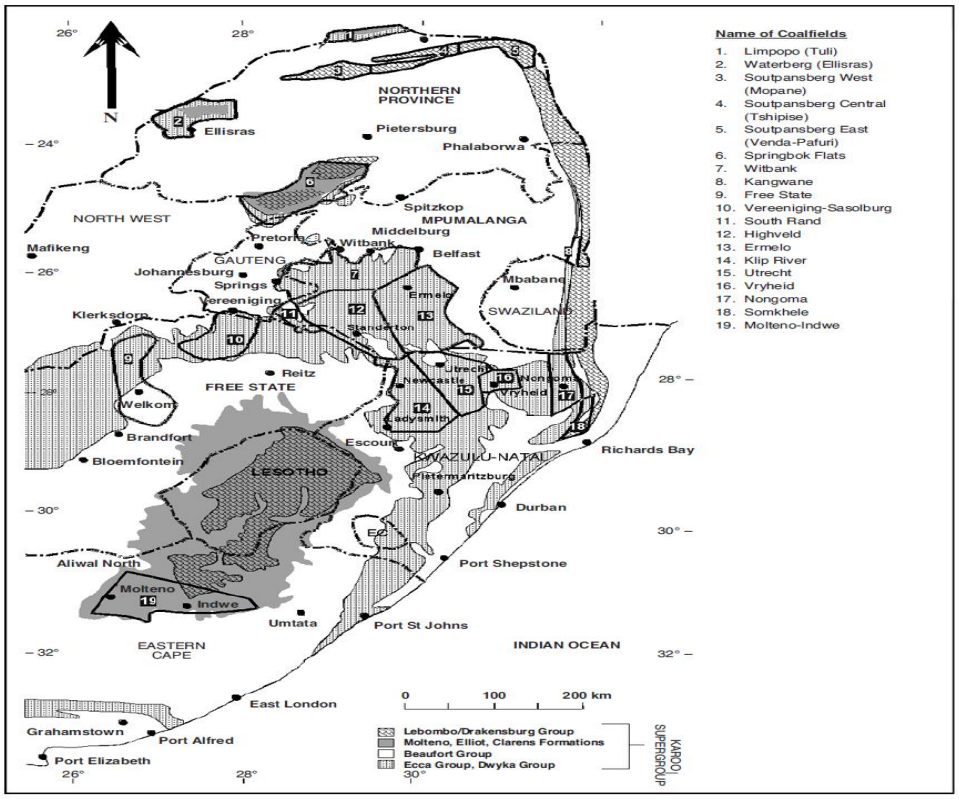

Figure 4 – Coalfields in South Africa (Jeffrey, 2005)

In the Witbank coalfield, there are up to seven coal seams of different coal qualities. According to the quality characterization summarised by Jeffrey (2005), there are zones with good metallurgical coal in certain seams. In some areas of the Witbank coalfield, the No. 1 seam is a source of high grade steam coal suitable for export after beneficiation. This seam also contains coal with a very low phosphorus content that makes ideal metallurgical feedstock. The No. 2 seam is also known to contain very good quality coal that is suitable for low ash metallurgical purposes and/or export. In contrast, the seam No. 4 is known to be dull and of a lower quality whilst the No. 5 seam has been mined as a source for metallurgical purposes (Jeffrey, 2005). The products from this coalfield are generally obtained by beneficiating whole seams and extracting the high quality products for metallurgical purposes or exports whilst leaving middle quality products for power generation and export as steam coal to the Middle and Far East (Holland, 1989).

The Highveld coalfield has lower quality coals with some seams used for metallurgical applications and yet others for power generation and export. The bulk of the coal in this coalfield, however, is owned and utilised by Sasol for coal-to-liquids in the Fischer-Tropsch process.

The No. 2 seam in the Highveld coalfield contains low grade coal with calorific values of between 20-23 MJ/kg. However, in some areas of the coalfield, the No. 2 seam has excellent washability characteristics that allows for a calorific value exceeding 27.0 MJ/kg at favourable yields above 70%. The No. 4 seam is generally of a low quality (CV – 20 - 25 MJ/kg, Ash 20 – 35%). However, the upper parts of this seam are known to have much higher ash content (~40%) and lower calorific values (<20 MJ/kg). The 4 Upper seam has great variability but is also generally of a low quality. The No. 5 seam is of a better quality with in-situ calorific value in excess of 25 MJ/kg (Jeffrey, 2005).

In summary, in the quest to establish whether other coals exist that could be used to produce semi-coke similar to Exxaro's product, it would appear that there could be suitable non-coking or metallurgical coals in the Witbank / Highveld coalfields that could rival the semi-coke produced currently from the Waterberg coalfield (specifically the Grootegeluk Mine).

This research project seeks to test a number of coals from the relevant coalfields by undertaking in depth characterization of all the coals in order to establish their suitability for producing a semi-coke such as the Exxaro product. This will also establish the commercial advantages (or not) that a producer of such semi-coke products will have.

2.3 Marketing Strategy

Steve Jobs famously once said "Build it and they will come". Whilst this may have worked exceptionally well for Jobs and the Apple family, it certainly is not the case in most instances. With the implementation and embedment of most new products, there has to be a strong focus on market and the needs of the market. This very simple concept is applicable to all products from mining to pharmaceuticals to banking and household products to mention just a few.

According to West et al. (2010), "marketing is an activity that continues to rely largely on the successful generation, dissemination of, and response to market intelligence". Marketing is also not a single, one-time event. To ensure the sustainability of the product in the market, requires strategic marketing research with the aim of understanding competitive advantages of the product and to possibly create new advantages.

Semi-coke was developed by Exxaro to act as a component of the reductant blend in the ferroalloy industry. This was largely possible due to the characteristics of the product and the fact that it could so easily substitute traditional chars and cokes that are being used by local ferrochrome producers.

Whilst the product has proved to be successful in its current application, it has become necessary to understand the threats that face semi-coke in the development of the marketing strategy for the future.

It was the process of determining marketing strategy that led to the development of this research project. One of the factors of strategic marketing management is strategic analysis. This is described by West et al. (2010) as the analysis of the macro conditions, competitive environment and the internal environment. This research will touch on all these aspects but will focus predominantly on the internal environment and the understanding of the product i.e. to establish robust strategy in consideration of the technical abilities of the semi-coke. This is further supported by a need to understand what makes the Exxaro semi-coke superior in performance and whether coals from other coalfields can produce a similar product.

These factors would have strong relevance for the ongoing marketing strategy to be undertaken by the company and for the manufacture of this special product. This will be discussed further in brief at the close of the Research Report.

3. METHODOLOGY

The following chapter details the methodology followed in the test work for this study as well as the standards applicable and the equipment used. This includes the determination of physical, chemical and maceral composition of the semi-coke and the products of the other test coals as these elements play an important role in the kinetic behavior of coal during the process of "charring" or semi-coke manufacture.

3.1 Sample Collection

This study focused on the testing of coals from the Waterberg, Highveld and Witbank coalfields. Eight samples were obtained for testing, two (2) from the Waterberg and six (6) from typical metallurgical seams in the Witbank and Highveld coalfields as listed in Table 2 below. Metallurgical seams are usually characterised by their low ash, low sulphur and low phosphorus contents. The first exception was Sample D which was selected as an alternative to typical metallurgical coal i.e. Sample D was specifically selected to understand whether semi-coke could be produced from a high ash thermal coal.

Table 2 - Sample Identification of feed coals

Sample	Coalfield
A	Highveld
B	Highveld
C	Witbank
D	Witbank (Delmas)
E	Witbank
F	Waterberg
G	Waterberg
H	Witbank

Of the two coal samples that were obtained from the Waterberg coalfield. Sample F was typically a thermal coal produced from the upper benches that has

a very high ash content and is supplied into the power generation market. This sample was also deliberately selected to understand the impact this would have in the production and subsequent use of semi-coke.

Sample G was the Exxaro coal sample that is used as feed-stock to produce semi-coke. This semi-coke is under investigation and against which the other coal samples and their "semi-cokes" would be compared. Current semi-coke product provided the baseline for this investigation.

To ensure completeness, it was also necessary to obtain a sample of the locally produced *market coke* that is currently used in local ferrochrome production. This sample was obtained from the producer directly. *Market coke* is produced from a blend of coals and no precursor coal that is used in the production of market coke was available.

The following methodology was used in obtaining the samples.

- All coal samples were taken in accordance with acceptable ISO and SANS standards by suitably qualified practitioners at the respective mines.
- Samples were taken (where practically possible), from belt cuts, falling streams as stockpiles are built in order to avoid compromised material on the surface of the stockpile.
- All sample analysis was compared to historical production analysis to avoid outliers that can skew reporting. If the sample analysis was vastly different from the typical production analysis, then another representative sample was taken.
- 50kg – 80kg samples were taken in all instances. These were further split for analysis as required.
- All samples (coals and cokes) were secured in sample bags with cable ties to prevent excessive drying out or oxidation of the samples and any contamination.

Every precaution was taken to ensure the robustness of the samples secured. The samples were then taken to the Exxaro Metallurgical Services division for additional preparation and testing.

3.2 Sample Preparation and Analysis of Feed Coals

The samples were weighed and a Particle Size Distribution (PSD) was determined. The coal samples were split and then sent for the following tests to determine the composition and properties of the coal.

The splitter (as seen in Figure 5), was used to provide a representative sample from the original feed samples. These smaller samples were then utilised for the specialised testing

Figure 5 – Splitter (Exxaro)

A 3kg sample of the original coal sample was utilised for the proximate analysis, full ash analysis and for sulphur and phosphorus testing, as listed in Table 3.

Table 3 – Test Methods

Analysis	Standard
Proximate Analysis	
Inherent Moisture	ISO 331:1983
Volatile Matter	ISO 562:1988
Ash Content	ISO 1171:1997
Fixed Carbon	By calculation
Total Sulphur	ISO 334:1992
Phos in Coal	
Ash Composition (XRF)	XRF
Roga Index	ISO 335:1974

The coal samples also underwent basic Roga Index tests to determine their caking properties. This test was completed to fully eliminate any doubt as to the nature of the coals selected. The Roga Index test is ideal for this purpose as it is relatively inexpensive and does not require sophisticated equipment to indicate the caking potential of the coals. If the Roga tests had indicated good caking potential, then additional tests to determine the free swell index, fluidity and dilatation would have been considered to determine the nature of the specialised coking potential in the coals.

A 1kg sample of the original coal were submitted for petrographic analysis. These samples were further crushed to -3mm for this analysis using the crusher captured in Figure 6 below.

Figure 6 – Cone Crusher (Exxaro)

The coal petrographic analysis was conducted by the Exxaro accredited coal petrographer. Petrographic analysis is the determination of the microscopic "building blocks" of coal, namely the organic components (or macerals) and inorganic components (or minerals) and the degree of maturity or rank of the coal (Crelling, unknown). The latter factor is measured by the percentage reflectance of light off the surface of one of the organic macerals, vitrinite. Blocks of 7x8cm were prepared in accordance with the ISO Standard 7404-2, 1985 requirements. The polished surfaces of the blocks and multiple coal particles embedded in the blocks were then examined using reflected light microscopy and oil immersion objectives.

The petrographic analysis was carried out using a Leica DM2500P microscope with an S&M PMT Photometry System in accordance with ISO 7404-3, 1994 standards.

Petrographic analysis provided the following information:

- Maceral content (proportions of the maceral groups: Vitrinite, Liptinite and Inertinite)
- Mineral Matter (proportions of the mineral groups)
- Vitrinite Reflectance (R_oV)

3.3 Sample Preparation and Analysis of Charred Product

Mechanical screens (as per Figure 7 below), were used to screen out 13-15 kg of the -22mm +19mm fraction of each coal sample. This specific fraction is required for chemical analysis and to undertake the "charring" of each coal sample for the further determination of CSR and CRI.

Figure 7 – Mechanical Screening Equipment (Exxaro)

Each screened coal sample underwent proximate analysis, ash analysis and determination of sulphur and phosphorus content. These results were then compared with the results from the unscreened coal samples. A representative sample may be expected to have good correlation between the screened and unscreened coal samples.

After the analytical and caking tests had been completed, the coal samples were placed into the lab scale furnace for the "charring" or devolatilisation process to take place. The coals were put into the coal holder as seen in Figure 8 before being placed in the lab scale furnace (as seen in Figure 9). Thereafter the Coke Strength after Reaction (CSR) and the Coke Reactivity Index (CRI) were determined. These tests were performed at Bureau Veritas in accordance with ISO Standards.

Figure 8 – Coal Holder (Bureau Veritas, Lab Scale)

The Coke Reactivity Index (CRI) is calculated as the percentage weight loss of the coke sample after reaction with carbon dioxide to form carbon monoxide.

The Coke Strength after Reaction (CSR) test is calculated based upon the amount of reacted coke that forms during the CRI tests.

A traditional locally produced *market coke* sample and an Exxaro *semi-coke* sample underwent the same analysis for comparative purposes.

Figure 9 – Charring Equipment (Bureau Veritas, Lab Scale)

The "charred" samples were sent back to Exxaro Metallurgical Services for further evaluation. There the samples underwent the adapted MICUM test or Tumble test for the determination of mechanical strength.

For this test, the "charred" sample is placed onto a sieve, with the mass retained at each screen size recorded. It is then loaded into a rotating drum and the drum is then rotated a 100 times. Once complete, the sample is then once again sieved with the mass retained at each screen being recorded.

The change in the mass retained on the screen that is less than 6.3mm is used as an indication of mechanical strength.

3.4 Petrographic Analysis of Charred Products

It is very important to determine the nature of the change in the coal particle as it devolatises and the influence on the structural transformation. To this end, the "charred" samples as well as the locally produced market coke and the semi-coke samples were prepared for petrographic analysis by the accredited Exxaro petrographer.

Once again and as with the coal samples, 7x8cm blocks were prepared to further analyse the "charred" particles including image analysis. These blocks are prepared in accordance with the ISO Standard 7404-2, 1985 requirements and are then examined using reflected light microscopy and oil immersion objectives.

For the image analysis, multiple representative portions of each coke sample were selected and prepared for optical microscopy by impregnating the sample with epoxy resin. Each block was then analysed using a Zeiss Axioscope A1 microscope (fitted with an automated stage). The carbon forms were classified on the basis of reflectance, anisotropy and morphology. The coke, or that portion of the coal that had softened, swelled and subsequently hardened, was identified as *binder phase* forms. The binder phase forms are produced from more reactive macerals that soften and react. The *filler phase* components are derived mainly from inertinite macerals that do not soften during carbonization.

In contrast, the binder phase forms consist of isotropic (smooth, unstructured texture) or anisotropic textures (crystalline-like textures). Of the latter, the following forms are found: incipient, lenticular, circular and ribbon like anisotropic carbons. In coke-making, it is the *binder phase* forms that soften and become more "plastic" as they bond the *filler phase* into a more cohesive structure that promotes stability and strength.

It was expected that the image analysis with reference to the classification of the binder and filler forms would provide insight into the nature of the coals and carbons required in the production of a comparable semi-coke.

4. RESULTS AND DISCUSSIONS

This chapter presents the results of the tests undertaken on the coals and the "charred" or semi-coke products investigated in this research. The results will be analysed and correlated where appropriate as discussion.

4.1 Feed Coal Characterisation

The tests include conventional analysis including proximate analysis, ash composition, total sulphur and phosphorus content, petrographic analysis to determine maceral content and reflectance and Roga Index tests.

4.1.1 Characterisation of Conventional Analysis

It is important to understand the constituents of the parent coal to determine the magnitude of impact these characteristics have on the charred samples thereafter. For this characterisation, conventional analysis techniques were performed on all coal samples. These techniques consisted of proximate, ash composition analysis (XRF) and total sulphur and phosphorus content.

The results from these tests are depicted in Table 4 below. They are reflective of analysis from the unscreened original sample. The feed sample was then screened and crushed (where required) to a +22-19mm size fraction. This specific sizing is required for charring tests to be completed. A representative sample of this size fraction then underwent conventional analysis i.e. proximate, ash composition analysis and determination of the total sulphur and phosphorus content. These results are shown in Table 5 below. It was important to complete these tests on both the unscreened and screened samples as it allowed for confirmation of quality differences due to size and, to some extent, repeatability.

All further reference to analysis will be in consideration of the screened analysis in Table 5.

Sample F was deliberately selected from a thermal bench in the Grootegeluk Complex that has high-ash coal (35.7%) with a low fixed carbon value. This was done to determine the impacts of using such a coal in a charring application for use in a commercial furnace. This coal is not traditionally beneficiated and also serves to explain the higher ash levels and the lower fixed carbon values in the Grootegeluk coal sequence. In addition, Sample D was selected as an alternative coal source or a known outlier without metallurgical properties. This is once again evident by the higher ash levels (17.9%) and phosphorus (0.030%) as compared to traditional metallurgical coal.

Calorific value is an important parameter in boiler applications. However, for the purposes of this analysis, the percentage fixed carbon is of greater importance in a ferroalloy application as this indicates the ability of the carbon to sustain the reductant necessary in ferroalloy furnaces.

Sample C and Sample G are prime metallurgical coals and as such do show the highest fixed carbon values. Samples H and A also show favourable fixed carbon levels. Sample E has a high volatile content (32.3%) and has been selected from a unique seam in the Witbank Coalfield that is recognised to be highly reactive and exceptionally high in vitrinite content.

Whilst phosphorus is an essential element to most aspects of the living world, it is not desired in the ferroalloy industry. Excess phosphorus in the feed coal transfers to the hot metal in a smelting application and will result in differential weaknesses of the metal. Typically the resultant metal is used in the production of stainless steel and can cause embrittlement which increases the hardness and ductility of the steel. These consequential effects and the severity thereof, has resulted in phosphorus being a primary consideration in the selection of feed coals (Internet: www.totalmateria.com).

Low phosphorus coals are classified as levels < 0.01%, medium phosphorus products are classified at > 0.01% < 0.1% with high phosphorus levels above 0.1%. For most metallurgical processes (including ferroalloys), a product of <0, 01% is desired. This is an extremely sought after product with most consumers willing to pay a premium to secure coal volumes. In consideration of the analysis, only Samples E, G and H can be classified as low phosphorus with Sample C coming in very close with a phosphorus level of 0.013%. Samples A and D are considered medium phosphorus coals whilst Samples B and F are high phosphorus coals.

Similarly, sulphur is an important consideration in the selection of the coal feed. Sulphur is known to impact the "toughness" of stainless steel making it very difficult to work with. It tends to make steel tender and brittle at high temperatures in rolling and forging operations (Internet: www.totalmateria.com). All samples meet the sulphur limit of < 1%. It is however desired that the sulphur content be as low as possible.

In terms of ash composition, all coals show very high silica and alumina oxides, with variable Fe_2O_3, CaO, MgO and SO_x. Alkali elements are naturally low in all South African coals. It must be remembered that a combination of high CaO and MgO in most heat processes in excess of 800°C will result in a reduction in the air fusion temperature and can lead to slagging.

The differences in the analysis of the parent coals and the screened products was found to be minimal. Perhaps the only significant difference is that the sulphur and phosphorus content was slightly higher in the screened fraction.

Table 4 - Coal Feed Analysis (Unscreened)

Sample Identification			A	B	C	D	E	F	G	H
Proximate Analysis	% Inherent moisture content	*(air-dried)*	4.1	3.4	2.3	3.9	4.1	1.8	1.3	2.4
	% Ash content	*(air-dried)*	14.5	15.4	15.5	19.1	14.6	32.8	11.3	12.1
	% Ash content	*(dry basis)*	15.1	15.9	15.9	19.9	15.2	33.4	11.4	12.4
	% Volatile Matter	*(air-dried)*	22.2	28.0	21.8	24.5	32.3	24.9	26.4	26.1
	% Volatile Matter	*(dry basis)*	23.1	29.0	22.4	25.5	33.7	25.4	26.7	26.7
	%Fixed carbon *(by calculation)*	*(air-dried)*	59.3	53.2	60.3	52.5	49.0	40.5	61.0	59.4
	% Total sulphur	*(air-dried)*	0.26	0.32	0.32	0.38	0.98	0.70	0.9	0.54
	Phos in Coal (calculated from P_2O_5)	%	0.036	0.177	0.013	0.043	0.008	0.11	0.010	0.005
Ash Composition (XRF)	Al_2O_3	%	33.49	26.45	34.36	33.73	27.65	28.71	31.86	27.88
	CaO	%	0.66	15.28	0.24	1.62	7.34	3.89	5.22	4.28
	Cr_2O_3	%	0.02	0.03	0.01	0.07	0.01	0.01	0.02	0.05
	Fe_2O_3	%	0.94	1.13	0.48	3.05	4.87	4.01	2.65	12.88
	K_2O	%	0.35	0.57	0.39	0.79	0.54	0.79	0.29	1.06
	MgO	%	0.38	4.56	0.16	0.67	2.33	1.29	3.24	0.92
	MnO	%	nd	0.10	nd	0.08	0.07	0.07	0.08	0.08
	Na_2O	%	nd	0.08	nd	0.07	0.38	0.09	nd	0.16
	P_2O_5	%	0.55	2.54	0.18	0.50	0.12	0.76	0.21	0.09
	SiO_2	%	61.22	42.39	62.28	55.85	47.84	55.44	48.21	46.91
	TiO_2	%	1.46	1.31	1.57	1.52	1.08	1.40	1.61	1.19
	V_2O_5	%	0.01	0.04	0.03	0.07	0.02	0.03	0.01	0.05
	ZrO_2	%	0.07	0.08	0.07	0.16	0.06	0.07	0.07	0.38
	BaO	%	0.18	0.42	0.07	0.06	0.16	0.17	0.09	0.05
	SrO	%	0.23	0.58	0.04	0.21	0.20	0.08	0.05	0.06
	ZnO	%	0.02	0.02	0.02	0.02	nd	0.02	0.03	0.03
	SO_3	%	0.42	4.87	0.24	1.58	7.23	2.48	7.53	2.70

Table 5 - Coal Feed Analysis (Screened - +28-19mm)

Sample Identification			A	B	C	D	E	F	G	H
			Coal (-28+19mm)							
Was the sample crushed			No	Yes	Yes	No	Yes	Yes	No	Yes
Proximate Analysis	% Inherent moisture content	*(air-dried)*	4.1	3.9	4.0	3.6	4.0	1.7	1.4	2.5
	% Ash content	*(air-dried)*	15.0	11.7	14.0	17.9	17.2	35.7	10.3	12.5
	% Ash content	*(dry basis)*	15.7	12.1	14.6	18.6	17.9	36.3	10.4	12.8
	% Volatile Matter	*(air-dried)*	23.5	27.7	24.6	24.4	31.7	24.5	25.6	27.1
	% Volatile Matter	*(dry basis)*	24.5	28.8	25.6	25.3	33.0	24.9	25.9	27.8
	%Fixed carbon *(by calculation)*	*(air-dried)*	57.4	56.7	57.5	54.1	47.2	38.1	62.7	57.9
	% Total sulphur	*(air-dried)*	0.75	0.38	0.61	0.43	0.97	0.68	0.70	0.64
	Phos in Coal (calculated from P_2O_5)	%	0.023	0.103	0.009	0.030	0.007	0.111	0.010	0.005
Ash Composition (XRF)	Al_2O_3	%	31.91	28.25	33.83	33.18	24.26	29.18	37.59	32.42
	CaO	%	0.50	11.11	0.28	3.42	8.11	3.28	0.23	4.10
	Cr_2O_3	%	0.06	0.02	0.02	0.02	0.02	0.01	0.02	0.06
	Fe_2O_3	%	5.38	3.45	2.69	3.18	6.36	3.99	0.62	4.49
	K_2O	%	0.38	0.48	0.54	0.65	0.65	0.77	0.36	0.78
	MgO	%	0.28	3.15	0.19	1.57	1.91	0.99	0.14	0.62
	MnO	%	0.03	0.11	nd	0.10	0.07	0.07	nd	0.08
	Na_2O	%	nd	0.10	0.02	nd	0.42	0.06	nd	0.13
	P_2O_5	%	0.34	1.94	0.14	0.37	0.09	0.71	0.22	0.09
	SiO_2	%	59.10	43.97	59.78	52.33	50.64	57.01	58.10	52.31
	TiO_2	%	1.50	1.40	1.72	1.70	1.13	1.26	2.03	1.38
	V_2O_5	%	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.07
	ZrO_2	%	0.07	0.06	0.09	0.09	0.07	0.07	0.10	0.12
	BaO	%	0.13	0.32	0.09	0.09	0.15	0.13	0.09	0.03
	SrO	%	0.14	0.44	0.05	0.14	0.19	0.07	0.05	0.06
	ZnO	%	0.02	0.01	0.02	0.01	0.01	0.02	0.03	0.01
	SO_3	%	0.46	5.25	0.20	3.54	4.85	1.36	0.38	2.27

4.1.2 Petrographic Analysis

Coal is characterised by its complexity in terms of grade, type and rank. The variations in these parameters are genetically related to the stages of coal formation. For instance, vitrinite is formed during anaerobic, reducing conditions by the leaves, plants and other plant material that is submerged under water through a process commonly referred to as gelification whereas inertinite is formed in aerobic sometime oxidising conditions. Therefore, as a result of differences in the chemical composition of the original plant matter and its environment of accumulation, followed by differences in diagenetic changes and metamorphism over time, coal displays many variations. These variations can only be adequately explained by means of petrographic analysis (Snyman, 1989).

Petrographic analysis includes the categorisation and classification of coals to indicate maceral characteristics as well as the reflectance measurements to determine the rank or the maturity of the coal. Maceral characteristics are very important parameters of coal and are divided into 3 broad categories i.e. vitrinite, liptinite and inertinite. The maceral type and its level of rank or maturity impacts upon the ultimate properties of the coal. (Falcon, 1986b; Hancox et al., 2014). The ratios of these maceral groups and the reflectance values of rank ensure that every coal particle is unique.

Falcon (1989), states that coals of the northern hemisphere possess very high vitrinite content (~80%) whilst coals of the southern hemisphere by contrast are in general characterised by high levels of inertinite. As stated earlier, this is due to the climatic and geological conditions existing at the time of pear accumulation. The coals in the Northern hemisphere (Laurasia) were formed in the water logged peat swamps and in equatorial conditions. In contrast, the Southern hemisphere coals were formed close to the end of an ice age in cold to

cool climatic temperatures with fluctuating seasons that were wet and dry and in highly variable topographical environments. (Falcon, *pers. com).*

In determining the rank or maturity of coal, the optical reflectance of vitrinite is used as it provides a very reliable measure of rank as the coalification process progresses irrespective of the proportion of macerals or minerals present (Falcon, 1989). Rank is a significant parameter for combustion whereby low rank coals are reactive to oxidation and combustion while higher rank coals ignite at higher temperatures. Prime coking coals that are used in the production of cokes occur in a significant but limited range of reflectance (1.0 – 1.6) as compared to blend coking coals (or caking coals) occur in the lower reflectance ranges. In addition, the temperature at which ignition and degree of devolitisation occur increases with increasing rank (Falcon, 1989). This is a significant physical property that can best be identified via petrographic analysis.

The petrographic analyses for this study were conducted on the relevant samples of the screened material that had been crushed further to the relevant particle sizing. The results can be seen in Table 6 below:

Table 6 – Petrographic Analysis of Feed Coal

Sample Identification	A	B	C	D	E	F	G	H
	Coal (-28+19mm)							
Vitrinite	20.30	26.60	12.50	21.00	55.20	31.70	25.00	26.40
Liptinite	3.00	2.30	5.40	4.50	4.60	7.80	3.60	3.10
Inertinite	71.40	67.30	76.40	68.50	33.70	41.50	66.80	64.80
Reactive Semi-Fusinite (RSF)	0.00	0.20	0.40	0.00	0.40	0.30	0.20	0.00
Total Reactives	23.30	29.10	18.30	25.50	60.20	39.80	28.80	29.50
Mineral Matter	5.30	3.60	5.40	6.00	6.10	18.70	4.40	5.70
Reflectance (RoV_{random})	0.679	0.685	0.691	0.688	0.687	0.686	0.690	0.683

The majority of the coal samples are characterised by significant quantities of inertinite (64,5% to 76%), with the exception of Sample E and Sample F where inertinite levels fall to 33.7% and 41,5% level. The latter samples are counterbalanced by higher vitrinite levels, namely, 55.2% and 31.7% respectively. High mineral was observed in sample F (18.7%) relative to all other coal samples who possessed less than 7% mineral matter. As previously mentioned, Sample F was deliberately selected from the high ash bench at Grootegeluk Mine. The vitrinite proportion is therefore low in all samples with the exception of Sample E with a vitrinite content of 55.2%.

Coals typically used to produce semi-coke are characterised by high levels of inertinite and consequently lower levels of vitrinite. Sample E was the anomaly within this sample suite (higher level of vitrinite, 55.2%). There have been numerous investigations undertaken on the Witbank coalfield including Falcon (1989) that have shown that there are parts of the Witbank coalfield that are characterised by higher vitrinite contents.

The rank of all the coals in accordance with ISO 11760 – 2005 procedures, indicates that the reflectance of vitrinite (RoV %) values place all coals within the rank of Ortho-bituminous or Medium Rank C coals. The mean random reflectance values of all coals fell within a close range, namely, 0.679 – 0.691 % RoV. The standard deviation confirmed the close range of the reflectance data indicating single seam origins without heat effect or blending by rank.

4.1.3 Roga Testing

This study was developed specifically for the evaluation of non-coking coals. To ensure the viability of the study, a simple Roga Index test was performed on the feed coals. Roga testing evaluates the caking properties of bituminous coals and is relatively cheap and quick to evaluate. Caking is an essential property for

the coking capability of coals and usually occurs in coals with a high vitrinite content.

The Roga Index for all coals indicated zero (0) caking properties. This is expected as the vitrinite content of all coals was too low. For a standard coking coal, a Roga Index of at least 45 is expected. For premium coking coals, this value can be as high as 90.

4.2 Charred Products, Market Coke and Semi-coke Characterisation

This section presents the results of charring tests performed on the feed coals as well as analysis of both *semi-coke* and *market coke* for comparison.

The current market place, ferroalloy producers utilise locally produced *market coke* as a reductant in their blends. In the recent past, the same market has recognised the merits of substituting the locally produced *market coke* with the Exxaro *semi-coke*. This is mainly due to the superior CSR and CRI properties of semi-coke. It was therefore important to conduct full comparative characterisation tests and analyses on both semi-coke and market coke products and then to compare them to the "charred" semi-coke look-alike samples to ascertain comparative suitabilities for the ferroalloy market.

4.2.1 Charred Analysis

The screened feed coals were "charred" to mimic the process to produce semi-coke and the resultant materials were tested for Coke Strength after Reaction (CSR) and the Coke Reactivity index (CRI). This included a sample of local *market coke* and Exxaro *semi-coke* currently supplied to the ferrochrome industry. The locally produced market coke sample was provided by the local producer from the final product stockpiles. Similarly, the semi-coke sample was obtained from the final product stockpile at the Exxaro Reductant Plant. The results thereof are as per Table 7 below.

The moisture of all samples decreased as the coals were heated. The locally produced market coke had a low inherent moisture at 0.3% as compared to semi-coke at 4%. However, all the other "charred" samples showed low inherent moisture contents of between 0.1% – 1.3%.

The locally produced *market coke* is produced from a blend of feed coals that includes low-ash coals (~10% ash) from Exxaro. Whilst a sample of the blended feed coal could not be obtained, it is apparent that the feed coal(s) must have been low in ash content to obtain a value of 15.4% in the final *market coke* sample. Similarly, the Exxaro semi-coke is produced from a feed coal with a variable ash content which can be as high as ~17%. The value of ash in the tested semi-coke sample was 18.3%. Both semi-coke and market coke samples are well within the specified range of supply to the ferrochrome industry.

Charred sample F indicated a very high ash content of 43.1%. This is expected as the feed coal is from a high ash thermal bench. Similarly, Sample D was selected as a replacement to metallurgical coal and also had a higher ash content. In terms of volatile matter content, it can clearly be seen that significant devolatilisation for all samples had occurred. This results in a concentration of the mineral matter in the ash content and in the phosphorus levels. This is most evident in Sample E which had a volatile content of 33% in the feed coal. Upon devolatilisation during charring, this resulted in an ash content of 28.9%.

The fixed carbon of all samples increased significantly with Samples A, B, G and H in the range of 80% fixed carbon. Sample F had the lowest fixed carbon content but this was expected given the origin of such high ash coal. The *market coke* fixed carbon was the highest at 83.1% with the *semi-coke* at just below 80%.

The phosphorus content of all charred coals increased but Sample C, E, G and H still displayed levels that are acceptable to the ferrochrome industry (below 0.014%). The market coke and semi-coke samples displayed very attractive phosphorus levels at 0.010% and 0.012% respectively.

With the exception of Sample E, all charred coals had sulphur levels within acceptable limits. The market coke sample indicated the second highest sulphur content at 0.82% whilst the semi-coke is at 0.50%. The market coke value is expected as one of the feed coals used in the market coal blend is obtained from the Exxaro Grootegeluk Mine and the sulphur content can be as high as 1.2%.

As seen in Table 6, Sample E also exhibited the highest level of vitrinite. According to Roberts (1988), "coals enriched in the vitrinite group macerals contain higher sulphur concentrations than high inertinite coals". This relationship can be explained by looking at the formation or early diagenesis of the coal in Figure 10 below.

Roberts (1988) explained that in periods of high water tables and pH in peat-forming environments with low redox potential, oxidative peat degradation did not occur while the vitrinite precursors were formed. Similarly, sulphate reductions occurred in this environment and resulted in higher H_2S concentrations that reacted with the iron and peat increasing the total sulphur content of the peat. In very much the same way, when the water tables were low, high redox potential favoured environments of aerobic respiration and very little H_2S was formed resulting in lower total sulphur content. Therefore a high vitrinite content correlated well with the higher sulphur content as can be seen in the feed coal Sample E and as demonstrated by the figure below.

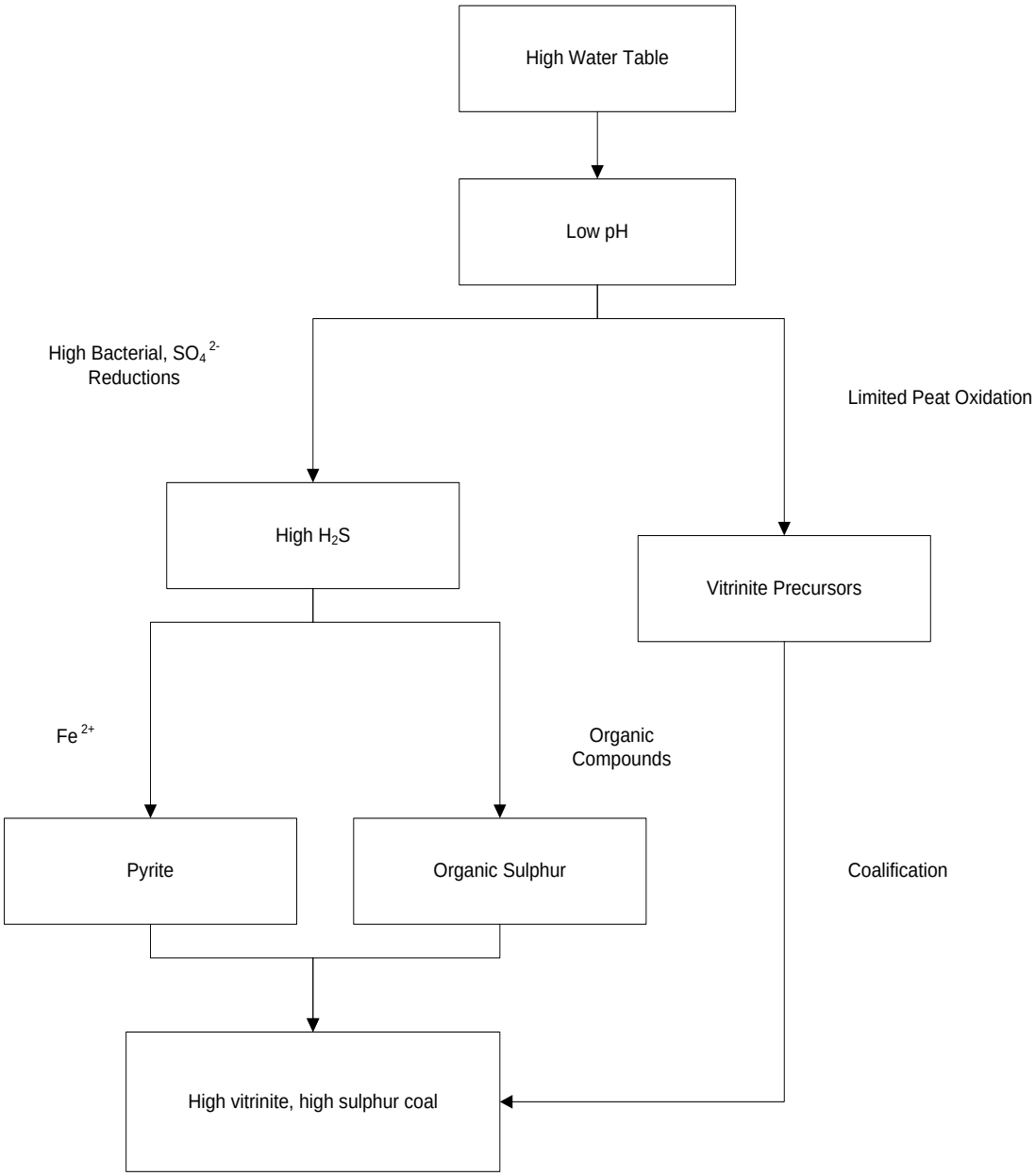

Figure 10 – Origin of high vitrinite, high sulphur formation coals (Roberts, 1988)

Table 7 – Charred Coal, Market Coke and Semi-Coke Characterization

Sample Identification			A	B	C	D	E	F	G	H		EXXARO SEMI-COKE	MARKET COKE (LOCAL)
			Coal (-28+19mm)										
Proximate Analysis	% Inherent moisture content	*(air-dried)*	1.2	1.3	0.8	0.6	0.1	0.4	4.1	0.5		4.4	0.3
	% Ash content	*(air-dried)*	19.6	18.6	20.6	22.7	28.9	42.9	13.9	17.4		17.5	15.4
	% Ash content	*(dry basis)*	19.8	18.8	20.8	22.9	28.9	43.1	14.5	17.4		18.3	15.4
	% Volatile Matter	*(air-dried)*	0.6	0.7	0.6	0.8	1.3	0.4	1.5	0.7		2.8	1.5
	% Volatile Matter	*(dry basis)*	0.6	0.8	0.6	0.8	1.3	0.4	1.6	0.7		2.9	1.5
	%Fixed carbon *(by calculation)*	*(air-dried)*	78.6	79.4	78.0	75.9	69.8	56.3	80.5	81.4		75.4	82.8
	% Fixed Carbon	*(dry basis)*	79.6	80.4	78.7	76.4	69.8	56.5	83.9	81.9		78.8	83.1
	% Total sulphur	*(air-dried)*	0.25	0.58	0.44	0.43	1.11	0.67	0.48	0.32		0.50	0.82
	Phos in Coal (calculated from P_2O_5)	%	0.040	0.151	0.014	0.040	0.012	0.165	0.013	0.009		0.012	0.010
Ash Composition (XRF)	Al_2O_3	%	30.73	27.31	34.50	34.25	24.22	30.39	34.75	32.10		34.59	18.26
	CaO	%	0.50	9.91	0.31	3.37	7.95	3.10	1.91	2.95		3.07	1.18
	Cr_2O_3	%	0.59	0.87	0.50	0.39	0.49	0.15	0.54	0.65		0.44	0.40
	Fe_2O_3	%	3.52	6.83	3.81	3.76	6.87	4.11	3.51	4.27		2.72	9.56
	K_2O	%	0.36	0.39	0.49	0.58	0.57	0.79	0.23	0.71		0.30	1.01
	MgO	%	0.25	3.07	0.22	1.43	1.93	0.81	1.13	0.47		2.36	0.83
	MnO	%	0.03	0.10	0.03	0.07	0.09	0.06	0.07	0.10		0.09	0.13
	Na_2O	%	nd	0.02	nd	nd	0.36	0.08	0.29	0.10		nd	0.02
	P_2O_5	%	0.46	1.84	0.15	0.40	0.09	0.88	0.21	0.12		0.15	0.15
	SiO_2	%	60.85	41.69	57.45	51.72	49.49	54.78	53.55	53.56		50.42	65.74
	TiO_2	%	1.41	1.22	1.51	1.73	0.91	1.46	1.98	1.45		1.65	1.89
	V_2O_5	%	0.02	0.02	0.02	0.03	0.02	0.04	0.03	0.06		0.03	0.14
	ZrO_2	%	0.07	0.06	0.07	0.08	0.06	0.07	0.09	0.10		0.07	0.21
	BaO	%	0.17	0.25	0.07	0.09	0.11	0.16	0.05	0.04		0.05	0.08
	SrO	%	0.18	0.36	0.05	0.15	0.17	0.08	0.05	0.05		0.03	0.04
	ZnO	%	0.01	0.02	0.02	0.01	nd	0.01	0.02	0.01		0.02	0.02
	SO_3	%	0.10	6.24	0.16	2.32	5.45	2.45	1.22	1.83		3.64	0.33
NSC	CRI	%	45.4	50.9	37.1	43.4	56.8	41.3	37.3	45.1		36.60	39.20
	CSR	%	27	42.3	54.9	40.5	24.0	26.5	53.8	40.5		51.50	36.80

4.2.2 CSR and CRI Determination

The most significant parameters to the ferroalloy industry remains the determination of the CSR and CRI as this measures the coke resistance to degradation and the impact of the reductant blend on the efficiency of the furnace. As noted in Table 1, the Exxaro semi-coke and the locally produced market coke had comparable CRI values. However the Exxaro semi-coke proved extremely favourable with a superior CSR to the locally produced market coke.

Of particular relevance is the fact that all of the coal samples that were charred were able to produce products that had comparable CRI values to both the locally produced market coke and semi-coke. With the exception of Sample C and Sample G, all other samples had a reactivity index that was higher than that of the locally produced *market coke*. However, Sample C and Sample G and the Exxaro *semi-coke* were only slightly lower than that of the locally produced *market coke* and were not low enough to be unique or problematic in a furnace application.

The results for CSR showed that with the exception of Samples A, E and F all other charred samples indicated a CSR far superior to that of the locally produced *market coke* and very comparable to that of the Exxaro *semi-coke*. The remaining samples (B, C, D, G and H) are likely to out-perform the locally produced *market coke* but are equal to Exxaro *semi-coke* in consideration of strength in delivering furnace stability.

From the figure below, it can be clearly seen that coals from the Waterberg, Highveld and Witbank regions can replicate the current Exxaro semi-coke and thereby substitute locally produced market coke if CSR and CRI were the only parameters to be considered.

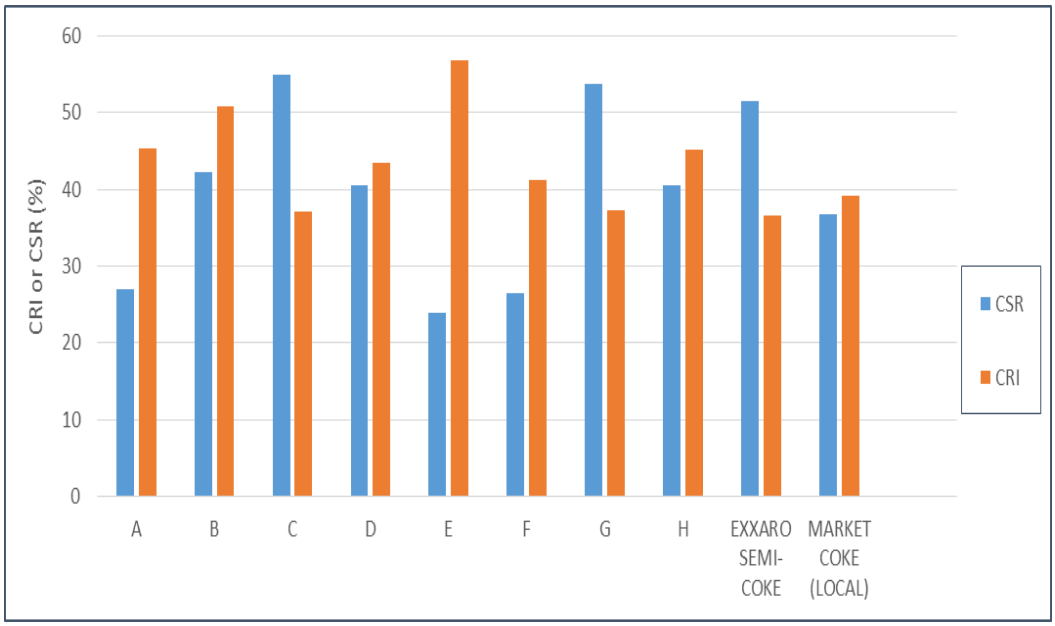

Figure 11 – CSR and CRI

4.2.3 Tumbling Test

After the coal samples had been charred, a small quantity of the sample was used to perform a tumbling test. This test has been adapted from the MICUM test and is an indicator of mechanical strength. The full results of these tests can be found in the Appendix. Table 8 below is a summary of the results.

Table 8 – Exxaro Tumbling Results – All Samples

	% Less than 6.3mm Before Tumbling	% Less than 6.3 mm after Tumbling	CSR (%)	% Increase
Sample A	0.46	11.72	27.00	11.26
Sample B	0.16	5.69	42.30	5.53
Sample C	0.03	2.04	54.90	2.01
Sample D	0.16	5.95	40.50	5.79
Sample E	0.43	7.08	24.00	6.65
Sample F	0.32	6.39	26.50	6.07
Sample G	0.25	3.52	53.80	3.27
Sample H	0.06	3.30	40.50	3.24
Exxaro Semi-Coke	0.00	1.32	51.50	1.32
Market Coke (Local)	0.07	0.76	36.80	0.69

CSR and the tumbling tests are both an indication of mechanical strength. In the graph below, Tumble 1 includes all data points whilst Tumble 2 excludes Sample E and F.

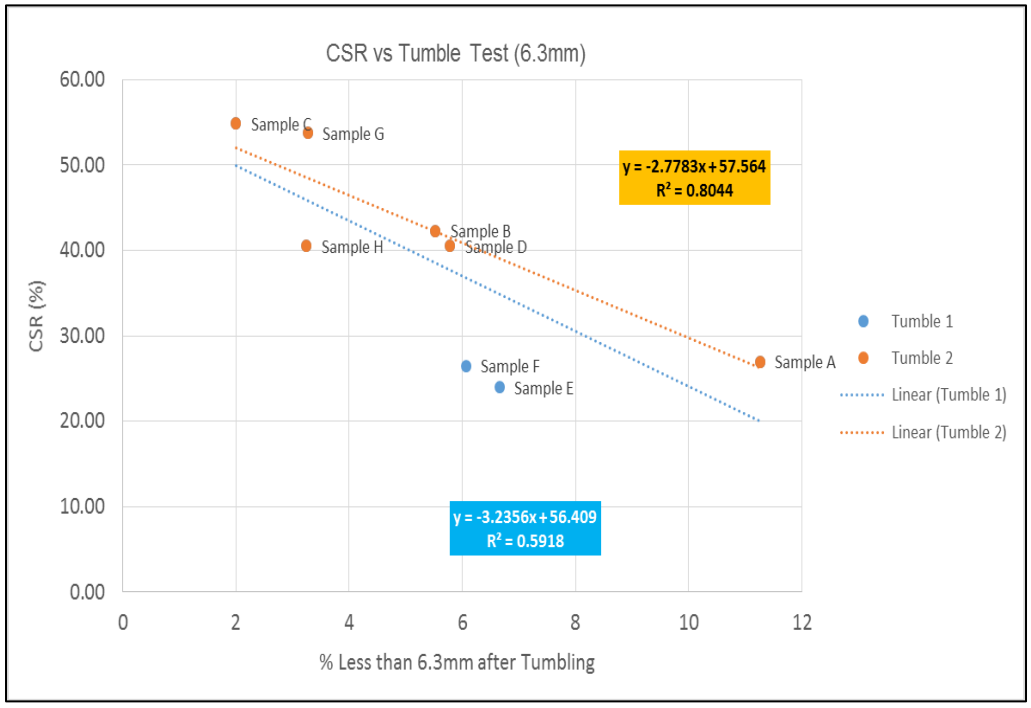

Figure 12 – Correlation between tumbling tests and CSR of charred coals

It can very clearly be seen from the results and the graphical representation above, that an increase in the percentage of material from screening after tumbling indicates a lower mechanical strength or CSR. The r^2 value of 0.8044 also indicates a relatively good correlation.

Sample E and F displayed high levels of vitrinite and lower levels of CSR. The higher levels of vitrinite resulted in more friable coal and can clearly account for the increase in breakdown and consequently the lower CSR levels. If the outliers of Sample E and F are excluded, then the r^2 is much higher and clearly indicates a relationship between determined CSR and the amount of material left on the screen after tumbling.

In addition, Sample A was obtained from shallow seams and this could have resulted in potential oxidation. This would increase the friability of the coal (increase breakdown of material) and thereby decrease the strength.

Components such as porosity, moisture content, weathering and oxidisability determines physical properties and can add to the variability in the coal. The impact of these factors and the variability they can cause can be clearly observed in the r^2 value.

4.2.4 Petrographic Analysis of Charred Coals

It was important to verify if there is a distinct relationship between the maceral contents of the coal and the resulting CSR and CRI values of the charred coals. To this end, several graphs were plotted below to indicate maceral content against CSR and CRI parameters. A trend line was also plotted incorporating all data sets. A trend line is most reliable when the r^2 value is closest or equal to 1. This is known as the coefficient of determination.

A second trend line for each graph is used to indicate a more meaningful data set if the outliers are excluded. This is indicated by the suffix 2 in the legend descriptor. In this instance, Sample F and Sample E will be omitted. Sample F was selected from a typical high ash coal seam and is not beneficiated. Sample E is an anomaly with very high vitrinite levels.

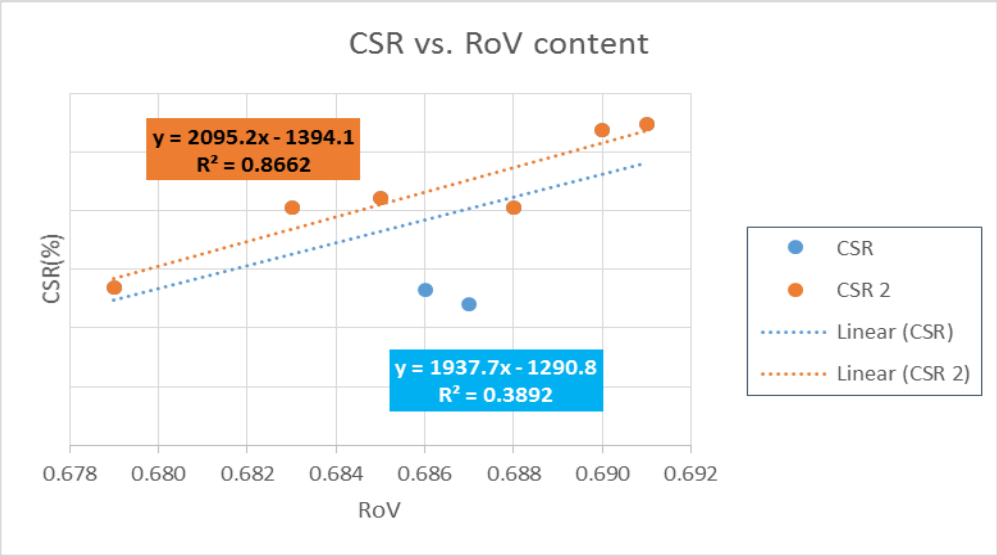

Figure 13 – CSR vs. RoV

If all the data points are to be considered, then there is a weak correlation between the CSR of the charred samples and the vitrinite reflectance of the low ranking coals. However, if we exclude Sample E due to the high levels of vitrinite in the feed coal and Sample F for the high ash levels in the feed coal, then there is a good correlation between RoV and CSR. In this instance, the CSR increases with increasing RoV.

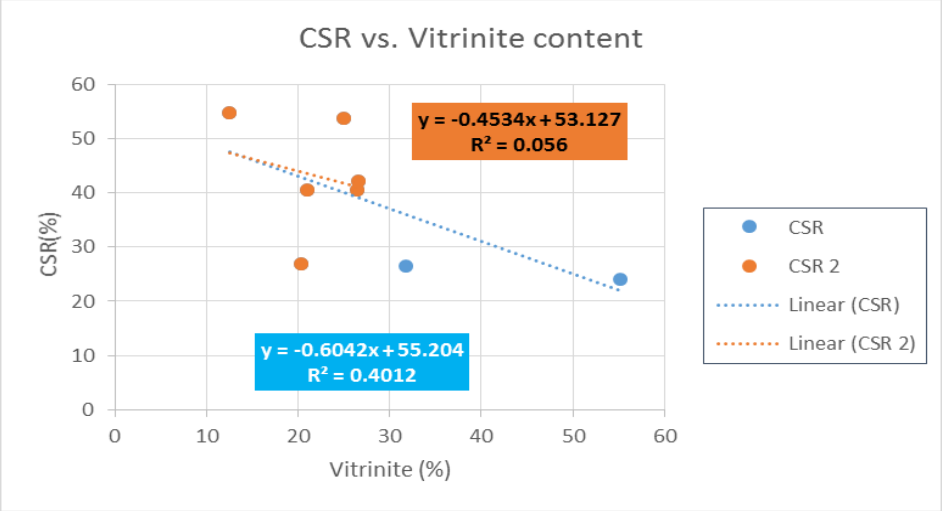

Figure 14 – CSR vs. Vitrinite

Diez (2001) reported a strong and close relationship between the CSR index and the vitrinite content of coal but that review was strictly around coke structure and properties and does not hold a correlation for this work. Once again, if Sample E and F are excluded, it can be clearly seen that there is no correlation between the vitrinite content and CSR.

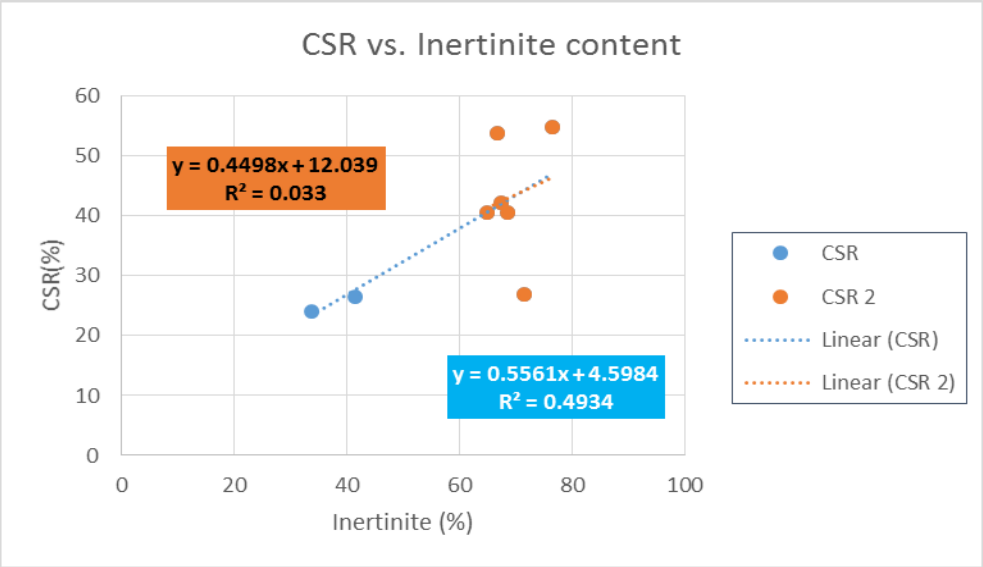

Figure 15 – CSR vs. Inertinite

Similarly, there is no correlation between the level of inertinite found in the feed coal and CSR if Samples E and F are excluded. If all the data points are to be considered, the correlation is weak and only distorts the influence of inertinite.

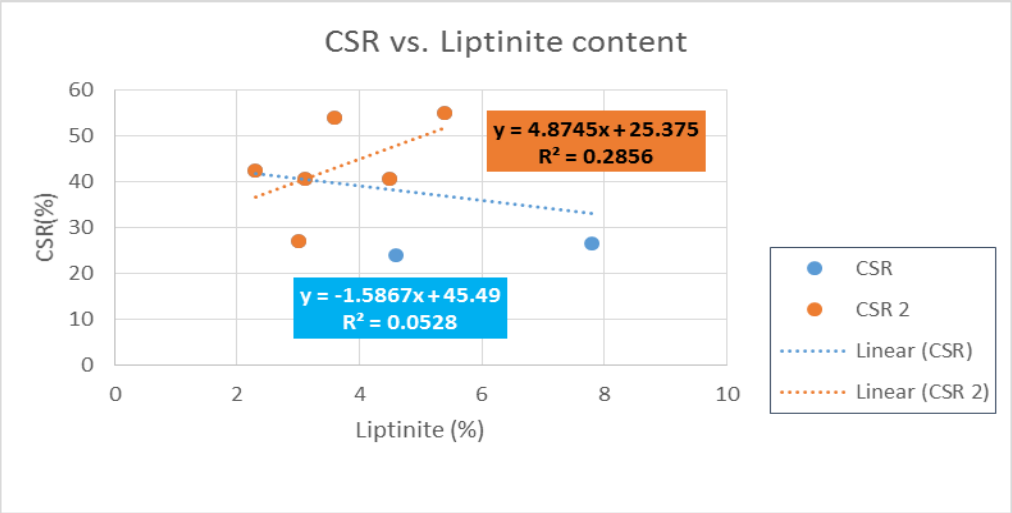

Figure 16 – CSR vs. Liptinite

There is an extremely poor correlation between liptinite and CSR for all data points and even with Sample E and F removed.

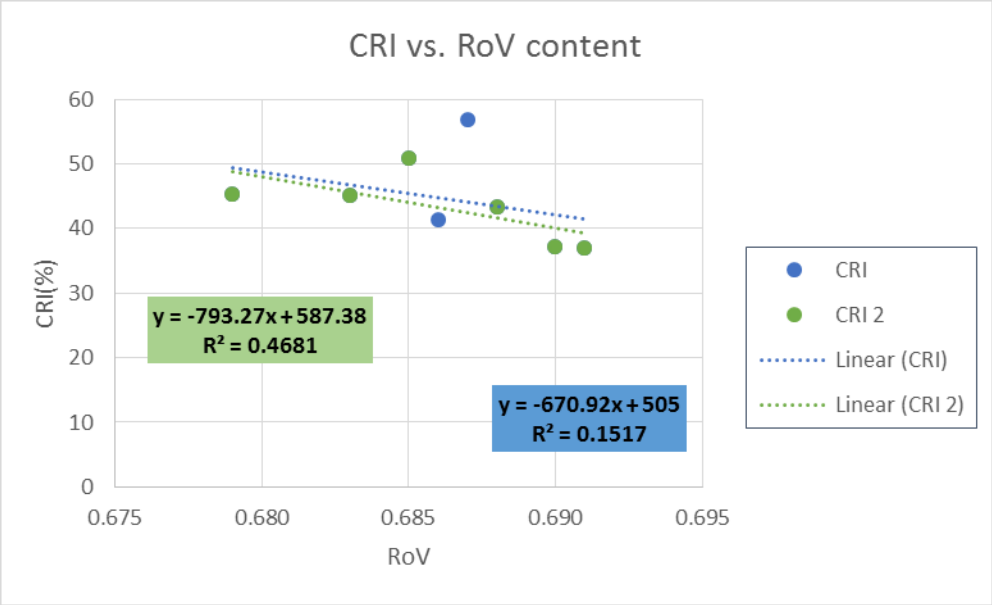

Figure 17 – CRI vs. RoV

It would appear that reflectance of vitrinite cannot be used to accurately predict CRI in charred coals even with the exclusion of Samples F and E.

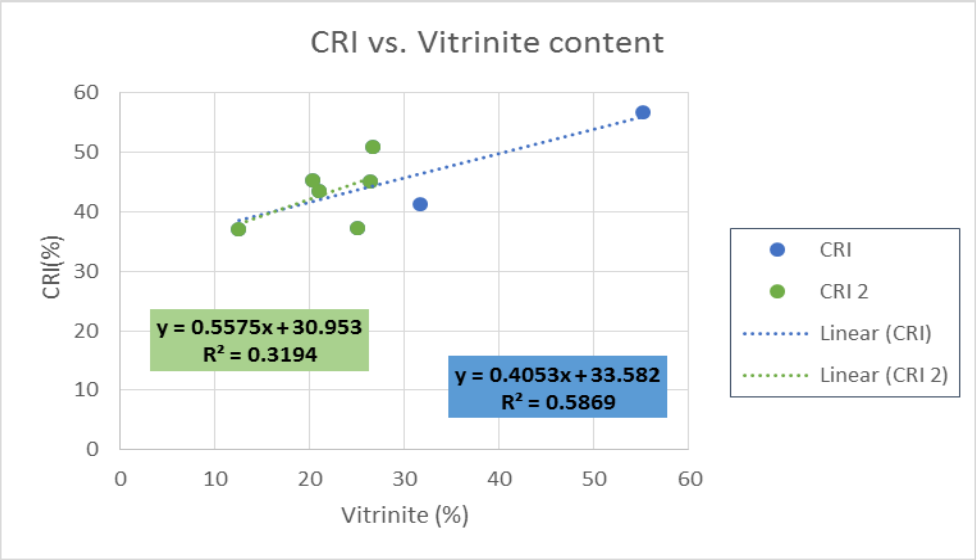

Figure 18 – CRI vs. Vitrinite

In early work done on characterisation of macerals, it was found that vitrinite has the lowest carbon content but the highest oxygen content as compared to liptinite and inertinite. (Crelling, unknown). This possibly means that vitrinite does promote better reactivity as it contains more oxygen which is necessary for combustion. Whilst this is still not a strong correlation, it begs further investigation.

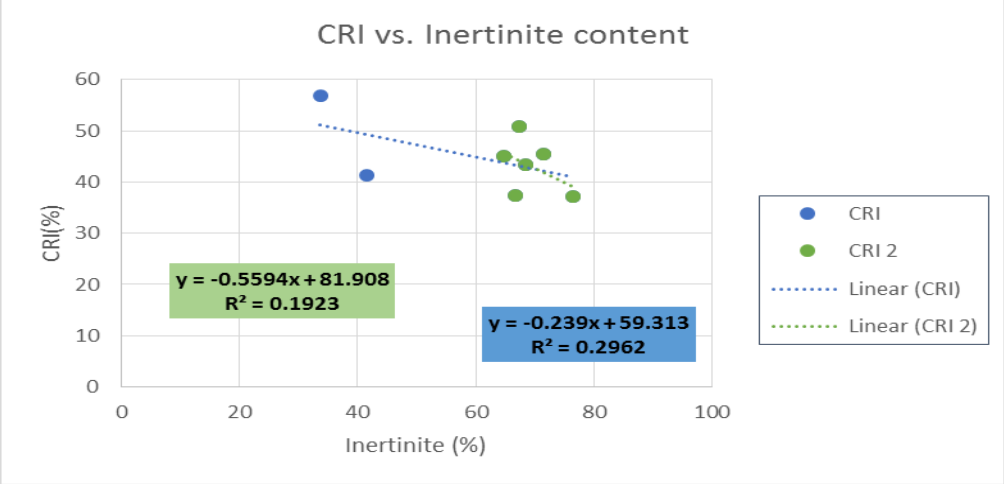

Figure 19 – CRI vs. Inertinite

There is a poor correlation between the CRI and inertinite content with the limited or full set of data points.

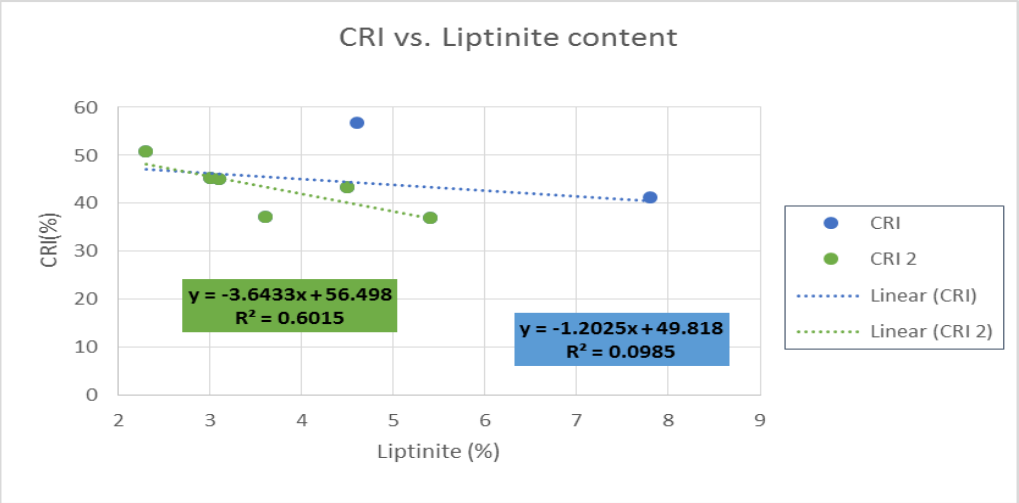

Figure 20 – CRI vs. Liptinite

If the outliers (Samples E and F) are excluded, then there does appear to be a correlation between the liptinite levels of the feed coal and the reactivity of the charred material. It does appear that the lower the inclusion of liptinite, the higher the CRI of the charred coals. However, the quantity of liptinite present is very small and is therefore not a strong indicator of a robust relationship.

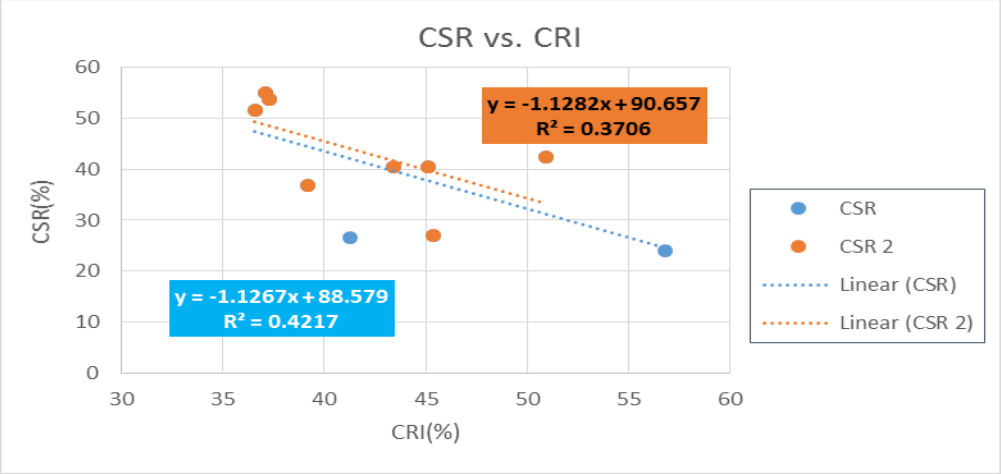

Figure 21 – CRI vs. CSR

In consideration of all the samples including the Exxaro *semi-coke* and the locally produced *market coke*, there appears to be some correlation between CSR and CRI but it is not conclusively defined. This correlation is expected. In most metallurgical blast furnace applications, a high CSR value is accompanied by a low CRI value illustrating an inversely proportional relationship and a very high degree of correlation (Diez, 2001). This is not the case with the samples under review and their application to a ferrochrome furnace. These is because the currently investigated coals used are non-coking, non-caking coals of a vastly different rank and structure.

In consideration of all the above data, it can be seen that there are no clear indicators of relationships or clear correlations between the maceral content of the charred coal and the CSR and CRI indexes of the same material.

4.2.5 Feed Coal Proximate Analysis Relationships with CSR and CRI

It is also important to understand the nature of the relationships (if any) between the proximate analysis of the feed coals with the charred coal parameters of CRI and CSR. Once again, several relationships were graphically represented with a trend line indicating the strength of the relationship between the selected variables.

The initial trend line includes all coals and the second line (with the suffix 2 in the legend), excludes Sample F. Unlike the previous representations, Sample E is included as the feed coal analysis does not display any unusual characteristics. However, Sample F is clearly a high ash coal extracted from a high ash coal bench and is a deliberate outlier in the selection of the coal samples. Therefore, only Sample F will be excluded in the second trend line (with suffix 2).

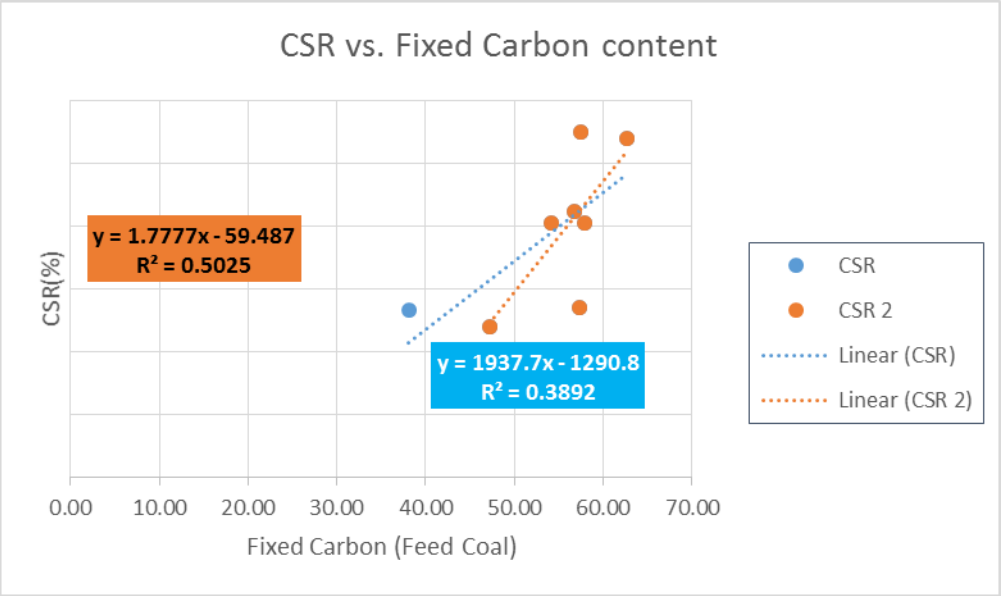

Figure 22 – CSR vs. Fixed Carbon

It can be seen from the graph above that if Sample F is excluded, there is a weak correlation between the fixed carbon levels and CSR.

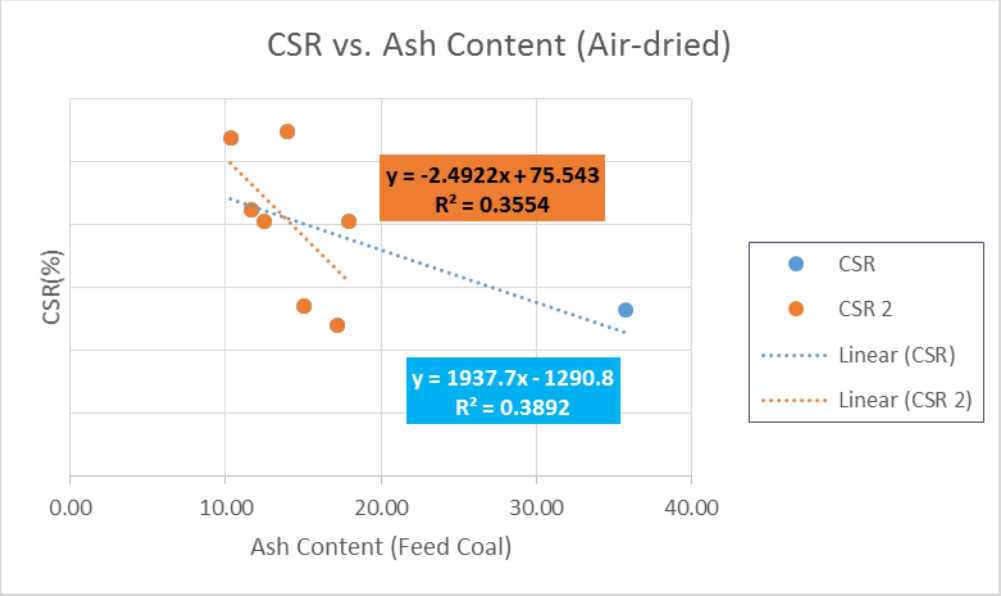

Figure 23 – CSR vs. Ash Content (Air-dried)

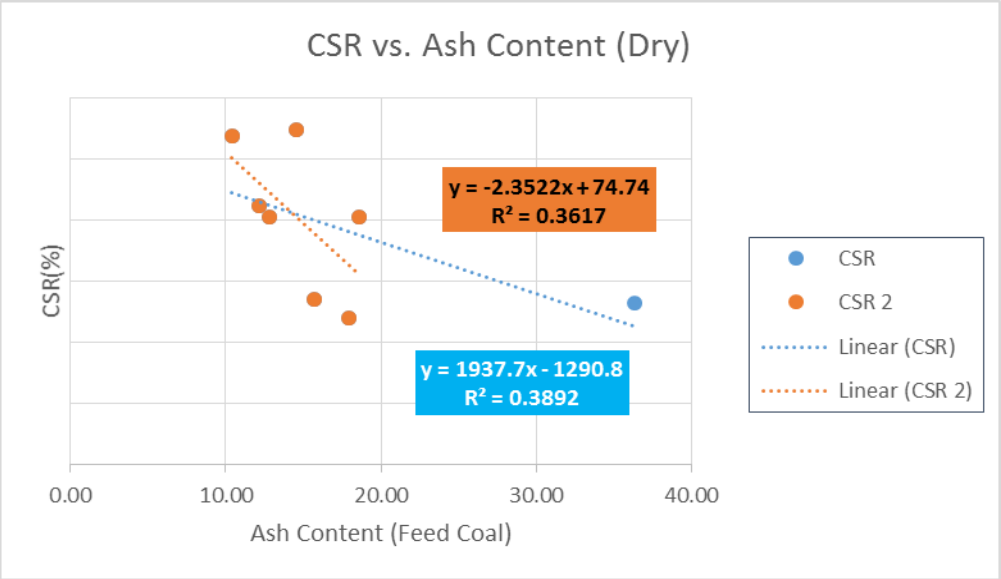

Figure 24 – CSR vs. Ash Content (Dry)

Figures 23 and 24 above indicate ash content compared to different bases i.e. air dried and dry. The results are similar but the relationships in both instances are poor and do not indicate any relationship between CSR and ash content.

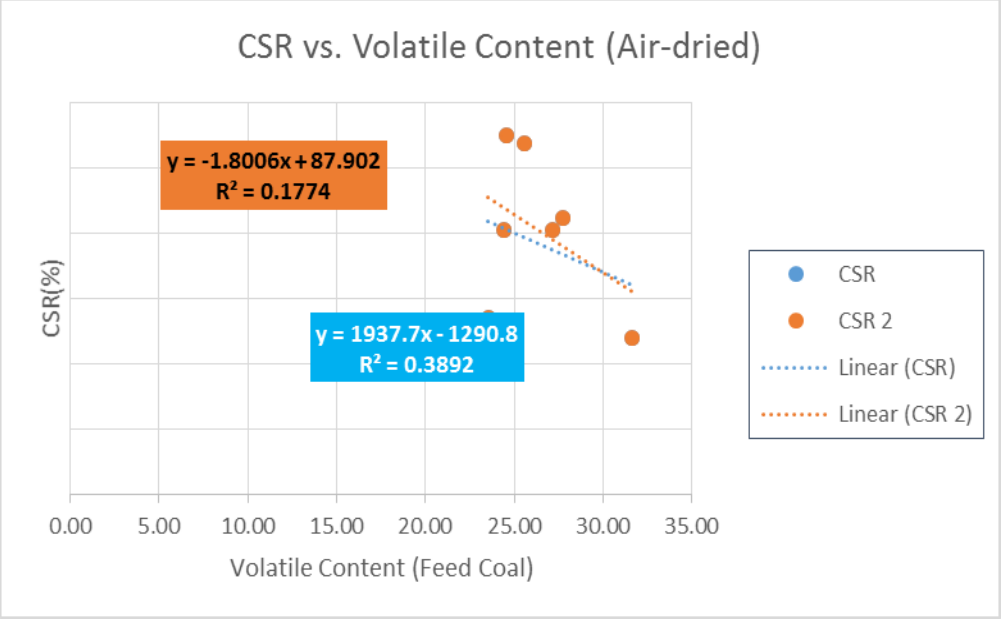

Figure 25 – CSR vs. Volatile Matter Content (Air-Dried)

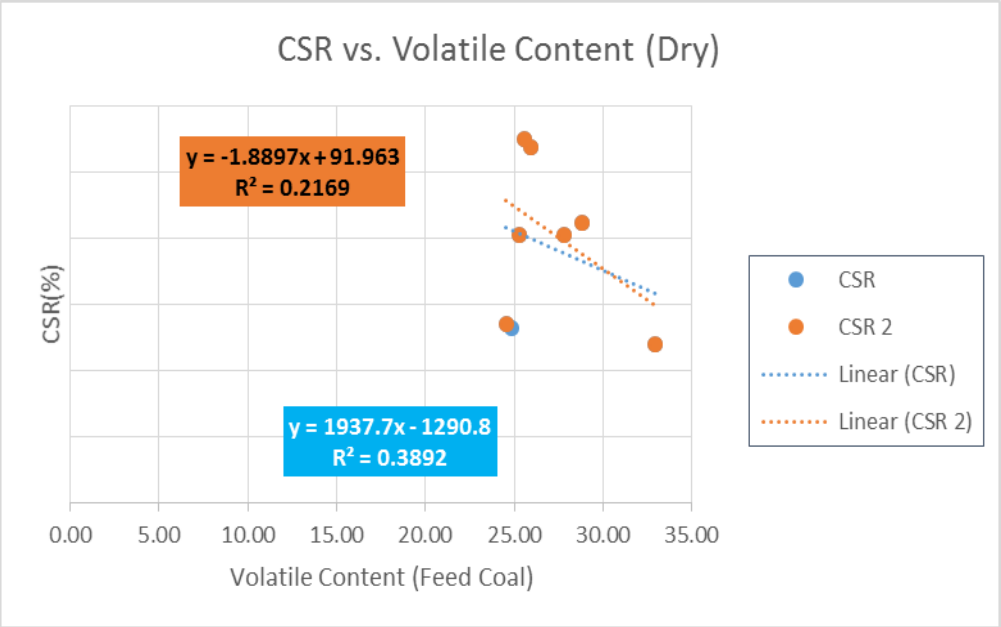

Figure 26 – CSR vs. Volatile Matter Content (Dry)

Similarly, the graphs above also show very poor correlations between the volatile matter content and CSR. This is as expected as coals release volatile matter on heating and as such do not contribute to the strength of the coal particle.

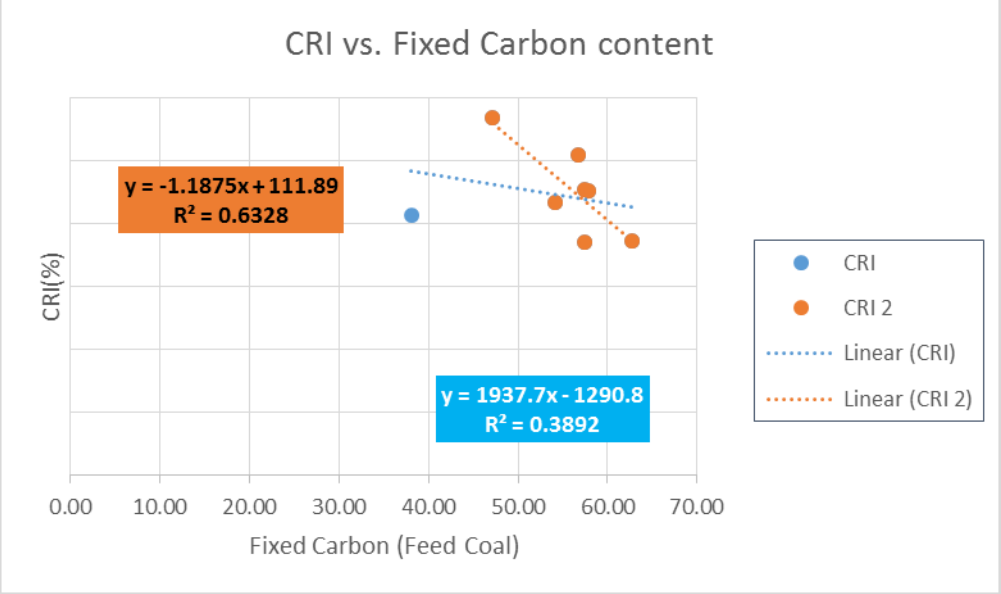

Figure 27 – CRI vs. Fixed Carbon

With the exclusion of Sample F, it can be seen that there is some correlation between the fixed carbon and CRI whereby the CRI decreases as the fixed carbon content increase. This is believed to relate to the increasing inertinite content which itself has a high carbon content.

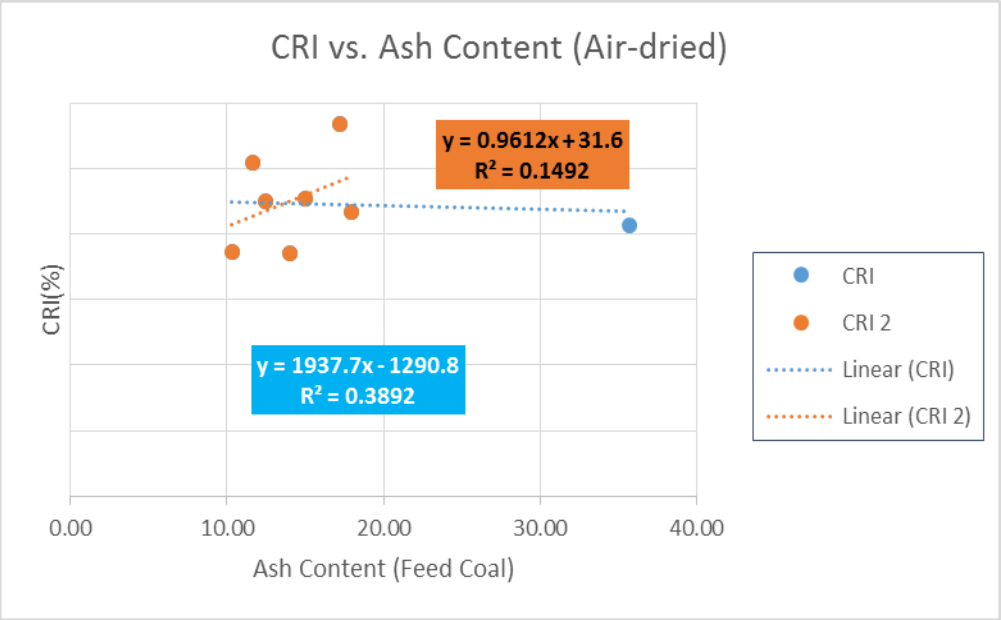

Figure 28 – CRI vs. Ash Content (Air-dried)

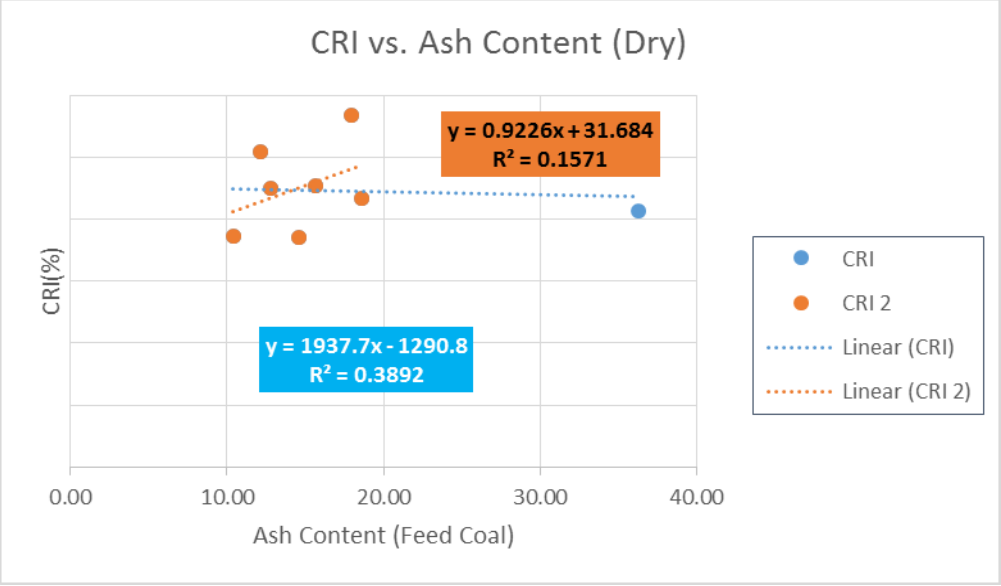

Figure 29 – CRI vs. Ash Content (Dry)

The graphs above show poor correlation between CRI and the ash content on an air-dried or dry basis. However, it can be expected that coals with a very high ash content would impact the reactivity of a particle as ash is unreactive.

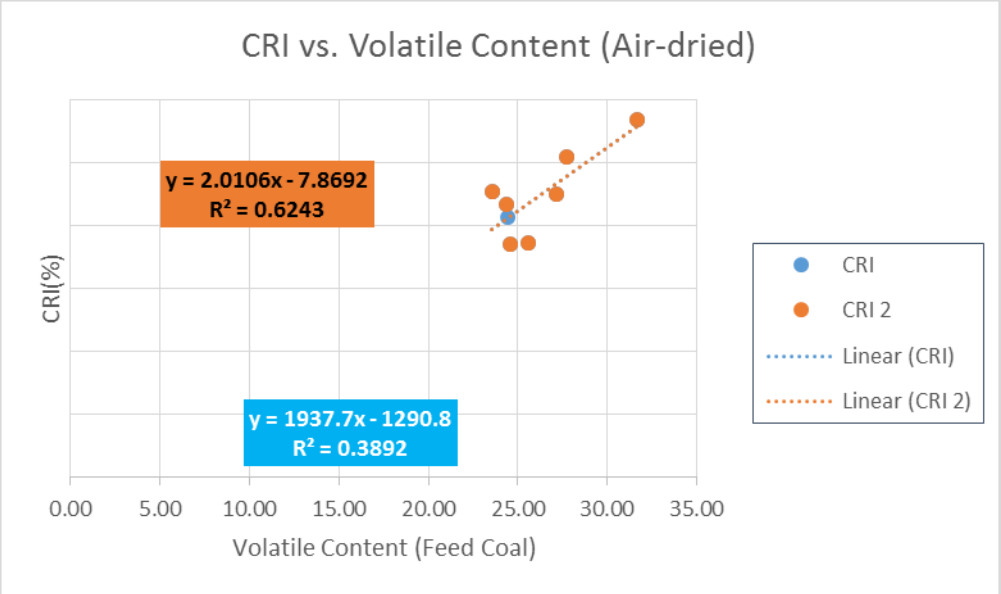

Figure 30 – CRI vs. Volatile Content (Air-dried)

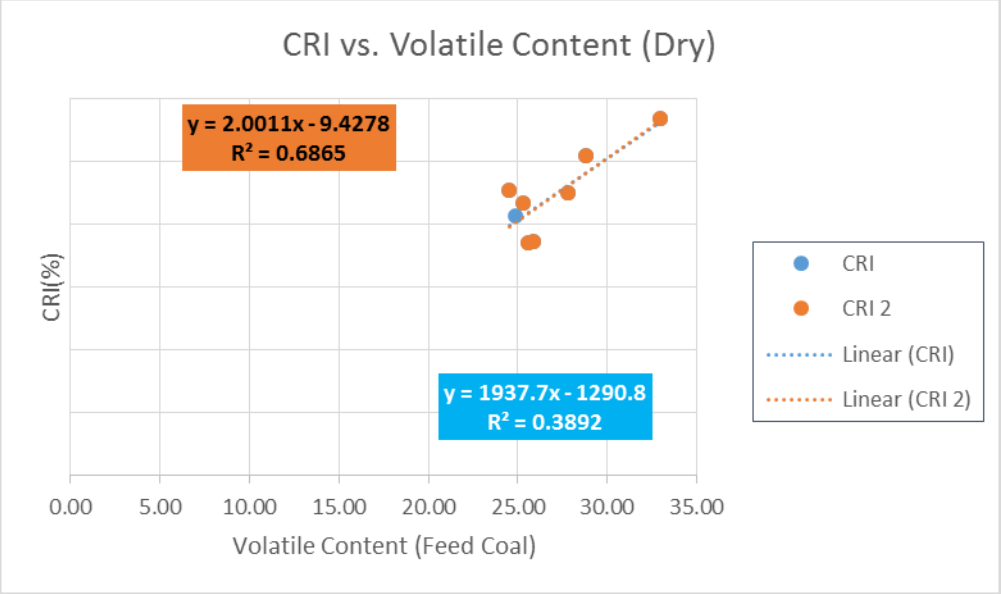

Figure 31 – CRI vs. Volatile Content (Dry)

The graphs above do show a correlation between the reactivity and the volatile content on both an air-dried and dry basis. This can somewhat be explained by the volatiles escaping during heating rendering the particle more reactive. This is further supported by the proportional relationship of the CRI index increasing for coals with a higher volatile content. This is inversely proportional to the fixed carbon content and inertinite content.

4.2.6 Coke Petrography

Diez (2001) stated that the importance of the physical properties of the "coke" is closely linked to the need to support the burden and to provide a permeable matrix through which the reducing gases can flow. These physical properties include the resistance to breakdown or the strength and abrasion. Diez (2001), went on further to discuss the structure of coke and its effects on coking properties. Whilst the study undertaken by Diez et al. was directly linked to the performance of cokes in a blast furnace application, there are definite similarities to coke used in smaller ferroalloy furnaces where the coke (albeit a lower quality), is also required to support the burden in the furnace.

This section specifically looks at the physical structures of the charred coals, semi-coke and the locally produced market coke to determine their effect (if any) on the CSR parameters utilising coke petrography and specifically image analysis. This microscopic examination of the samples can provide valuable information on the type of binder textures and the varying degrees of anisotropy depending on the rank and maceral content.

The reflectance of the charred coals was firstly determined and the results thereof are presented in Table 9 below.

Table 9 – Reflectance of charred coals

Sample Identification		Reflectance R_{rand}%	Sample Identification		Reflectance R_{rand}%
Sample A	1	6.266	Sample B	1	6.201
	2	6.579		2	7.150
	3	6.654		3	6.403
	4	6.408		4	6.117
	5	7.147		5	5.686
	6	6.486		6	5.738
	AVERAGE	**6.216**		**AVERAGE**	**6.216**
Sampe C	1	6.573	Sample D	1	6.116
	2	7.737		2	6.553
	3	6.419		3	5.889
	4	7.820		4	6.869
	5	6.274		5	6.519
	6	6.660		6	6.387
	AVERAGE	**6.914**		**AVERAGE**	**6.389**
Sample E	1	6.082	Sample F	1	7.051
	2	5.311		2	7.169
	3	5.778		3	7.064
	4	5.463		4	6.671
	5	5.505		5	7.000
	6	5.547		6	7.039
	AVERAGE	**5.614**		**AVERAGE**	**6.999**
Sample G	1	6.450	Sample H	1	5.928
	2	7.158		2	5.456
	3	7.305		3	5.959
	4	7.122		4	6.884
	5	7.692		5	6.449
	6	6.725		6	6.428
	AVERAGE	**7.075**		**AVERAGE**	**6.184**
Exxaro Semi-Coke	1	6.632	Market Coke (Local)	1	6.555
	2	6.964		2	6.892
	3	6.274		3	6.932
	4	5.827		4	7.089
	5	5.495		5	6.747
	6	5.740		6	6.347
	AVERAGE	**6.155**		**AVERAGE**	**6.760**

It must be remembered that the reflectance of the feed coals were 0.67 – 0.69. The large difference in the reflectance range of the coal relative to the charred particles indicates that the particles underwent massive structural transformation during devolatilisation. The reflectance range of the charred samples is between 5.614 and 7.025. While there is some variation between the mean reflectance values in the charred samples, the majority of the analyses are within this range. Cokes with a higher reflectance index usually have a higher degree of graphitization. According to Makhoba (2010), the reactivity of a material decreases with the degree of graphitization.

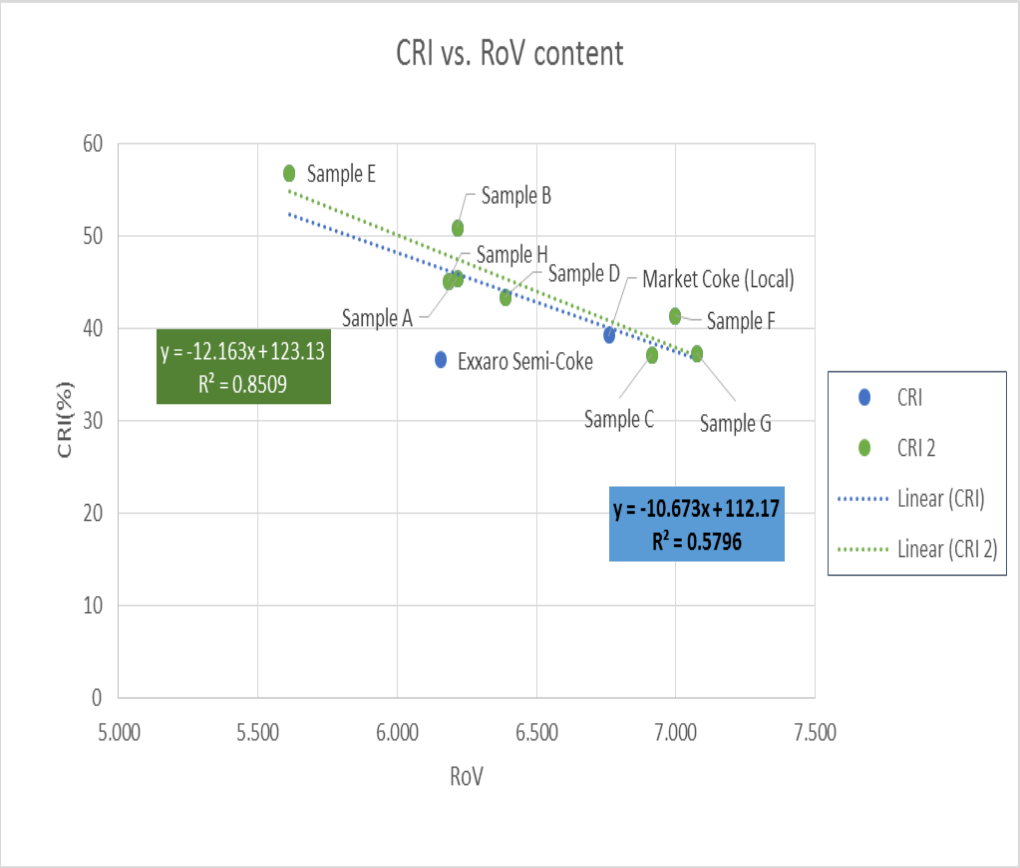

Figure 32 – CRI vs. RoV (Charred Coals)

This is expected as metallurgical cokes around the world typically present a low CRI with a higher reflectance or degree of graphitization. The samples of the Exxaro semi-coke and the locally produced market coke were produced in large scale commercial operations as compared to the coal samples charred in a lab scale operation. If these samples are excluded, then the correlation between CRI and RoV is much stronger as evidenced by the second trend line (with suffix 2). Therefore the CRI decreases as the RoV of the charred products increase.

Whilst it can be seen that transformation did occur, the results of the coke petrographic composition and textural analysis gave further insight into the nature of such transformation. The coke components of the petrographic analysis are classified as follows:

Filler Phase – this is mainly derived from the inclusions of inertinite group macerals that do not soften sufficiently during carbonisation. This includes inert semifusinite, fusinite, micrinite, macranite and inertodetrinite as well as minerals.

Binder Phase – this is represented by reactive macerals that soften and melt some passing through a plastic phase during carbonisation, sometimes encasing or even "glueing" together particles of inert filler material. The reactive macerals that pass through such phases include vitrinite, liptinite and (to some extent) reactive semifusinite. Such binder phase carbons, on heating, may develop different textural structures, ranging from isotropic (smooth non-crystalline forms) to anisotropic forms in which the textures may range from minor incipient crystallite structures to circular, lenticular and ribbon-like structures or "domains". Such anisotropic structures are well known in the prime coke making process. In the latter case, the filler forms are bound together by the binder phase to form a cohesive, continuous material, thus promoting size stability in the final product, prime coke. (Jordan, 2006).

For the image and textural component analysis, an average result (as shown in Table 10 below), was calculated from the results obtained from the individual portions. The results of all the individual portions can be found in the Appendix of this document.

Table 10 - Charred Coals Petrographic Composition – Textural Component Analysis (AVERAGE)

Sample Codes	A	B	C	D	E	F	G	H	Market Coke	Exxaro Semi-Coke
BINDER PHASE	**21.8**	**19.5**	**19.8**	**32.8**	**62.8**	**24.0**	**18.4**	**28.8**	**91.6**	**21.0**
Organic Inerts										
Fine (< 50 µm)	53.9	53.9	55.7	53.2	27.2	62.6	67.0	52.5	5.2	59.2
Coarse (> 50 µm)	21.4	25.3	22.9	12.8	7.0	11.7	14.1	16.1	0.1	19.1
Sub-total	75.3	79.3	78.6	66.0	34.2	74.3	81.1	68.7	5.4	78.3
Miscellaneous Inerts										
Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sub-total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Inorganic Inerts										
Fine (< 50 µm)	1.7	0.9	0.9	0.7	1.6	1.1	0.5	1.3	1.3	0.6
Coarse (50 µm)	0.9	0.1	0.2	0.3	0.6	0.5	0.0	1.2	0.7	0.0
Pyritic Minerals	0.3	0.1	0.0	0.2	0.9	0.1	0.0	0.0	0.6	0.0
Sub-total	2.9	1.1	1.0	1.1	3.1	1.7	0.5	2.5	2.6	0.6
FILLER PHASE	**78.2**	**80.3**	**79.6**	**67.1**	**37.2**	**76.0**	**81.6**	**71.2**	**7.9**	**78.9**
Depositional Carbons										
Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spherulitic	0.0	0.2	0.6	0.1	0.0	0.0	0.0	0.0	0.1	0.0
Pyrolytic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.1
Sub-total	0.0	0.2	0.6	0.1	0.0	0.0	0.0	0.0	0.5	0.1
Additive Carbons	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other										
Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Burnt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Sub-total	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0
MISCELLANEOUS MATERIALS	**0.0**	**0.2**	**0.6**	**0.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**0.1**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

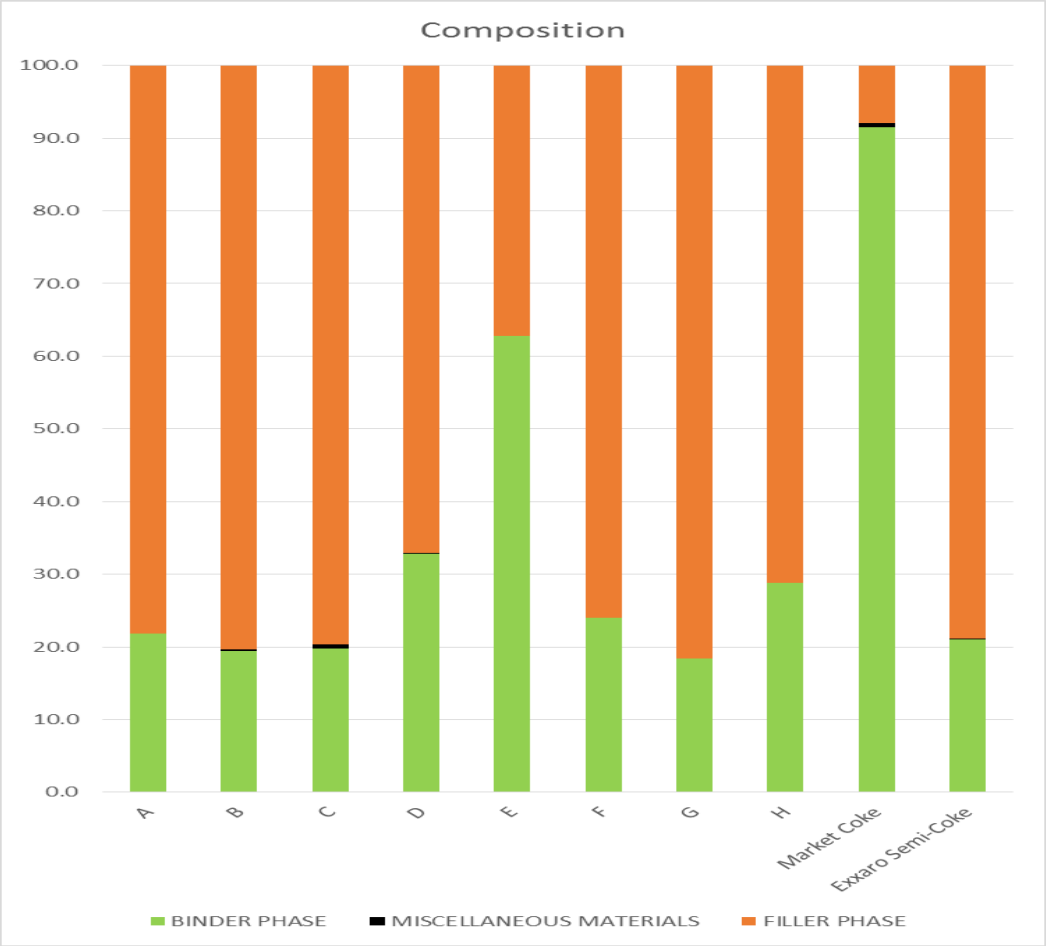

Figure 33 – Graphical Representation of binder and filler phases within all samples

Table 10 and Figure 33 above clearly show that the charred samples (A-H) indicate a variation in the composition between the samples as well as within the samples as well. The detail of this variation within the samples can be clearly seen in the Appendix of this report. The disparity can be explained due to the nature of the material used to produce the charred samples or as a result in the process of the formation (melting and solidifying). However, based on the average results above, the majority of the samples consist of filler material (>70%) generally occurring in the form of organic inerts (inertinite) and

inorganic inerts (clay and pyrite minerals). The high filler content is mainly due to the nature of the original coal material.

Sample E was the obvious exception and reflected the highest amount of binder. This can be linked to the maceral (vitrinite) content of the original coal sample. This relationship is also supported by the inclusion of reactive semifusinite matter as well. The r^2 value (as seen in Figure 34 below), indicates that there is a correlation between binder and vitrinite content as supported by theory of binder behavior. Similarly, Figure 35 indicates a positive proportional relationship between the amount of binder and CRI.

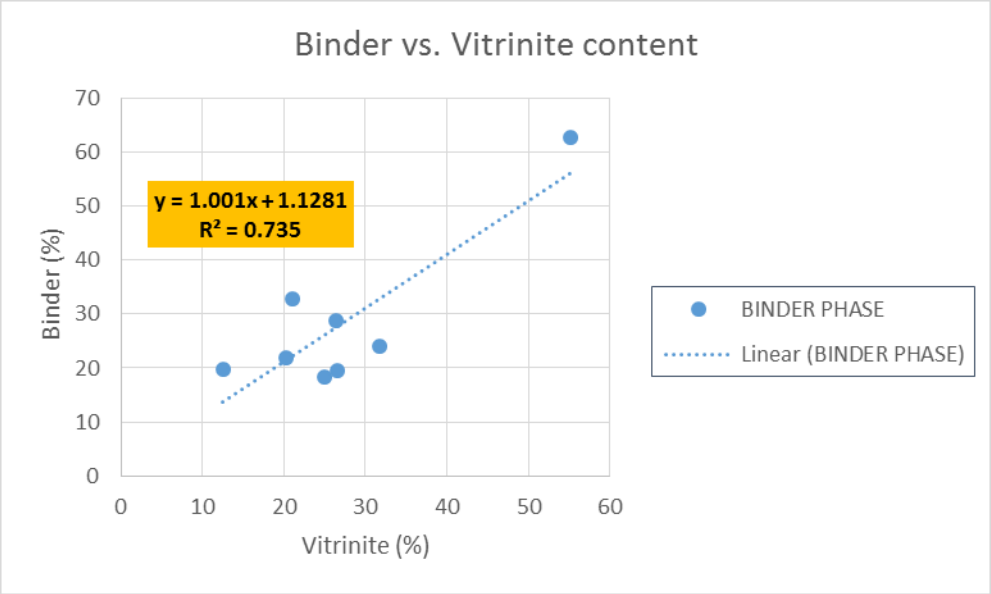

Figure 34 – Binder vs. Vitrinite Content

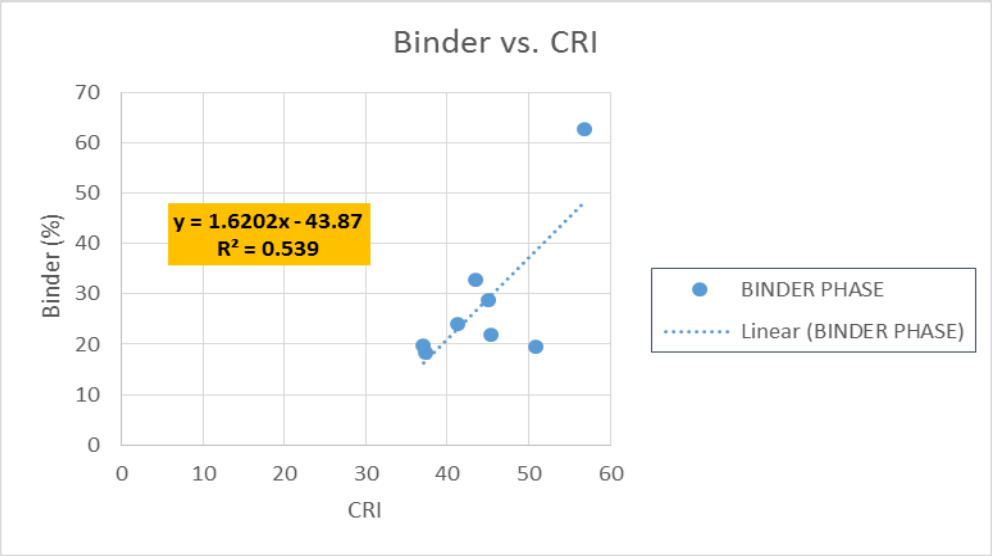

Figure 35 – Binder vs. CRI

The *semi-coke* is produced from a single source of coal and the resultant binder and filler phases closely correlate with the coal source, namely there is a higher filler content in both. On the other hand, the locally produced *market coke* possessed a predominant binder phase with much less filler. This latter result is attributed to the high vitrinite content of the coal blend with a high inclusion of reactives used to produce *market coke* in South. This result also correlates well with in-house test work that was completed in February 2015 by the Author and the Exxaro team. An excerpt of that analysis can be found in the Appendix – Table A1-7 of this document.

However, it is recommended that further investigation be applied to the role of binders and vitrinite content as well as the resultant effect on the CRI of the reductant.

In summary, in comparison to the locally produced *market coke*, the Exxaro *semi-coke* has an inordinately high proportion of material in the filler phase that can be attributed to increasing inertinite levels and fixed carbon.

It is also important to analyze the binder phase forms to perhaps better understand the structures of the carbons in the binder that can potentially impact CSR and CRI. To this end, all of the charred samples as well as the *semi-coke* and *market coke* were analysed. The table below shows the average result as calculated from the individual portions that form part of the Appendix.

Table 11 - Charred Coals Binder Phases – Textural Component Analysis (AVERAGE)

CARBON FORMS (Vol. %)	A	B	C	D	E	F	G	H	Market Coke	Exxaro Semi-Coke
BINDER PHASE										
Isotropic (from V7 or lower)	95.9	97.0	48.5	97.7	99.4	97.2	84.5	96.0	98.4	66.1
Incipient Anistropic (from V8)	2.4	0.6	6.5	1.1	0.6	1.7	5.1	0.5	0.3	6.6
Sub-Total	**98.2**	**97.6**	**55.0**	**98.8**	**100.0**	**98.9**	**89.5**	**96.5**	**98.7**	**72.7**
Circular Anisotropic (Granular)										
Fine (From V9)	0.5	1.6	12.5	0.6	0.0	1.0	4.1	0.7	0.6	8.1
0.5 - 1.0 µm										
Medium (from V10)	0.2	0.0	3.4	0.2	0.0	0.1	1.9	0.5	0.1	2.0
1.0 - 1.5 µm										
Coarse (From V11)	0.0	0.2	6.2	0.1	0.0	0.0	0.9	0.4	0.2	2.2
1.5 - 2.0 µm										
Granular Sub-Total	**0.8**	**1.8**	**22.1**	**0.9**	**0.0**	**1.1**	**6.9**	**1.6**	**0.9**	**12.3**
Lenticular (Leaflet) Anisotropic										
Fine (From V12)	0.8	0.7	14.2	0.3	0.0	0.0	1.3	1.8	0.3	6.1
width 1.0 - 3.0 µm										
Medium (from V13)	0.0	0.0	3.0	0.0	0.0	0.0	2.2	0.3	0.1	3.7
width 3.0 - 8.0 µm										
Coarse (From V14)	0.0	0.0	1.0	0.0	0.0	0.0	0.2	0.0	0.0	1.5
width 8.0 - 12.0 µm										
Lenticular Sub-Total	**0.8**	**0.7**	**18.3**	**0.3**	**0.0**	**0.0**	**3.7**	**2.1**	**0.4**	**11.3**
Ribbon (Flow) Anisotropic										
Fine (From V15)	0.2	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0
length 2.0 - 12.0 µm										
Medium (from V16)	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.6
length 12.0 - 36.0 µm										
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm										
Ribbon Sub-Total	**0.2**	**0.0**	**4.6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**3.6**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

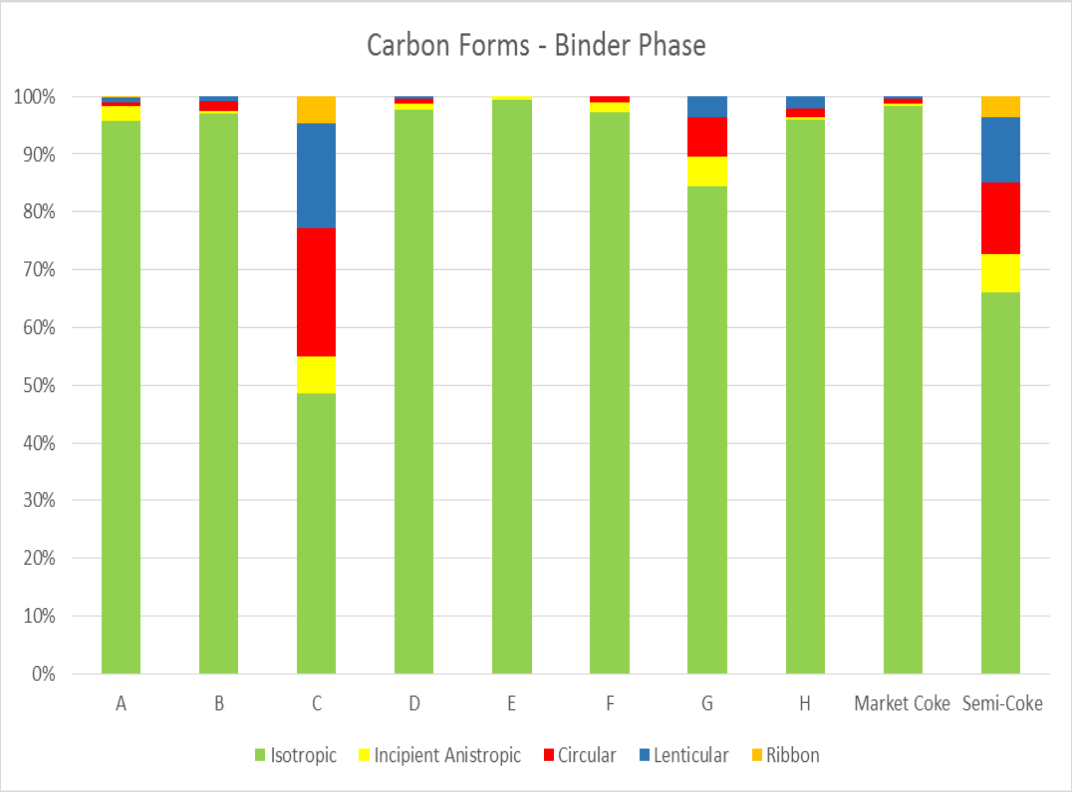

Figure 36 – Carbon Forms

As presented in Table 11 and Figure 36 above, the majority of the binder material is isotropic in nature, although some samples do show the inclusion of anisotropic structures.

Sample C and Sample G exhibit a substantial deviation from the typical isotropic forms of carbon in the binder phase displaying a wider distribution of anisotropic binder structures including circular, lenticular and some ribbon anisotropic forms. In metallurgical coke analysis, such terms are used to denote larger anisotropic structures. Such crystalline structures normally develop in coals of higher rank, i.e. those falling within or close to the prime reflectance category in the bituminous rank of coal. As such, these structures are found commonly in single and blended forms of coke. The fact that they are observed in these two

coals C and G is indicative of the inclusion of coals from a higher range of rank in the coals from those geological sources.

It can also be seen that even though Sample E has the highest vitrinite content and subsequently the highest inclusion of the binder, the quality of the binder was mainly isotropic. This is due to the lower rank of the coal i.e. lying below the prime coking coal range of reflectance.

It is of particular interest that the locally produced *market coke* was predominantly an isotropic structure whilst the *semi-coke* displayed variability with some anisotropic phases. Belinko (1982), stated that "cokes produced from bituminous coals owe their strength primarily due to the development of a anisotropic metaplastic phase which gives rise to the reinforcing network responsible for the strength of the coke". This structural change could explain why *semi-coke* has a higher CSR as compared to *market coke* and is so easily able to substitute traditional market coke in a furnace.

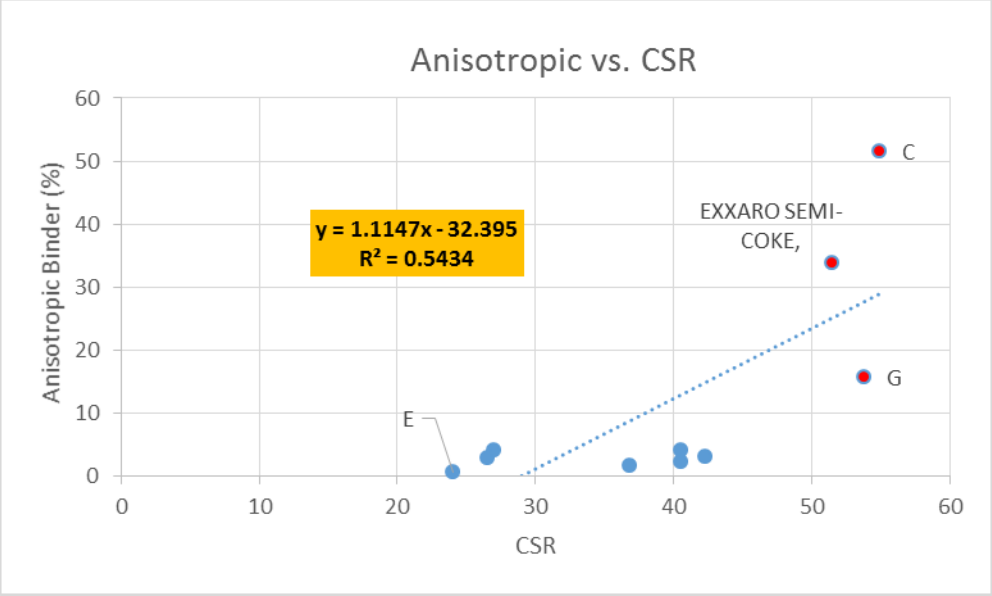

Figure 37 – Relationship between anisotropic structure and CSR

In addition, Samples C and G with the largest variation in binder phase carbon forms also had the highest CSR indices. Sample E with the least amount of binder phase carbon variations has the lowest CSR index. In consideration of Figure 38 above, this further supports that there is a correlation that suggests that anisotropic structures does influence the CSR of materials. This aspect requires to be investigated further.

4.3 Summary

This chapter has presented all relevant analysis and tests for both the feed coals and the "charred" or heated products with discussion on the relevance of such analysis to fulfil the objectives of this research. The key observations and conclusions are summarised in the next chapter.

5. CONCLUSIONS

Coals were selected from the Witbank, Highveld and Waterberg coalfields to determine their suitability in producing a semi-coke that can be significantly compared to the current Exxaro semi-coke and the locally produced market coke. These non-coking coals were technically evaluated utilising full characterisation techniques and petrographic analysis relative to key performance characteristics.

In terms of the prime research objectives as listed in sub chapter 1.1, the following observations and conclusions may be drawn in answer to the key questions approached in this research:

1. What are the key properties of the Grootegeluk Mine coal that contribute to the desired CSR / CRI?
    - Exxaro non-coking coal from the Grootegeluk Mine produce excellent semi-cokes with specific relevance to CSR and CRI.
    - Semi-coke (or charred coals) from Grootegeluk Mine possess anisotropic structures that contribute to higher CSR values. This demonstrates that the predominance of the anisotropic structures in the semi coke binder phase as well as the presence and predominance of inertinite in semi-coke, are key advantages.
    - The CSR of semi-coke is reported to provide better stability in a furnace operation relative to commercial *market coke*. The CRI for both products is, however, similar.
    - *Blast furnace coke* has a very strong inversely proportional relationship between CSR and CRI. There is also a very strong relationship between the CSR and the vitrinite content of the coal. In the course of this research, it was established that this was not the case with regard to semi-coke. This is due to the different organic (maceral) compositions and the

ranks of the feed coals. Prime coke is formed from vitrinite-rich coals at higher ranks thereby creating a hard, non-reactive reductant that only reacts in the hot liquid metal phase. Semi-coke on the other hand, is comprised predominantly of inertinite from coals in lower ranks. In this case, the semi coke thus formed is more reactive in the gaseous phase resulting in a good CRI whilst also providing great strength and therefore a good CSR.

- Coals with high volatile and ash content as well as high vitrinite levels was shown to result in semi-coke with low CSR values. If these samples are disregarded, then there is a strong correlation between RoV (vitrinite reflectance), inertinite content and CSR.

2. How do the CSR / CRI value of high ash coals (benches) from the Grootegeluk Mine compare with the semi-coke produced from the Grootegeluk Mine Bench 9 and 11?
    - As mentioned, coal Sample F was deliberately selected from the Grootegeluk Mine to understand the impact of a high ash bench on the production of semi-coke and specifically to the CSR/CRI parameters. In this case, it could clearly be seen that the CRI was still very comparable to Sample G. However, the CSR value was almost half that of Sample G. This clearly indicates that metallurgical coals are far superior in resultant CSR in semi-cokes.

3. How do coals in the Witbank and Highveld coalfields compare to the Grootegeluk Mine coal in the production of semi-coke in consideration of CSR / CRI?
    - Six (6) of the eight (8) coals that were tested were shown to have CSR and CRI indices that are acceptable to the ferrochrome industry. More specifically, semi-coke could be successfully produced from other coals in the selected coalfields with regards to the CRI within the reflectance

range of 0.67 – 0.69. This is based particularly on RoV utilising coal petrography.

4. If different, what are the different properties and performance characteristics between them?
    - The main difference between the semi coke coal source in the Waterberg relative to the Witbank and Highveld coalfields is that the high phosphorus and sulphur contents in the latter two coalfields are a barrier to entry for those semi-coke producers.
    - The availability of large volumes or reserves of such low sulphur and low phosphorus feed coal material to produce a comparable semi-coke from the Highveld and Witbank coalfields is very low. Most of this product (in large quantities) has been mined out in the past decades.

5. How will strategic advantage be determined from information obtained from this semi-coke investigation?
    - Based upon this investigation, it is apparent that Exxaro will remain the dominant player in the production of semi-coke due to their ownership of large volumes of suitable low ash, low vitrinite, low sulphur and low phosphorus coal material specifically suited for the ferroalloy market. The marketing strategy that could be adopted is to protect, defend and systematically grow the market thereafter via strategic expansion of the Reductants Plant.

In conclusion the following points may be made:

It terms of attempting to establish which factors controlled CSR and CRI, the observation was drawn that there is no single prominent parameter, or a relationship between two parameters, which controls these performance factors.

CSR and CRI appear to arise from a combination of a number of different factors and relationships that play a role, including the rank and maceral composition of the original coal, porosity (Okolo, 2014) and the degree of anisotropy in the binder that develops when the coal is heated. Given the importance of these performance factors, it is strongly recommended that these combinations be investigated further.

In terms of the hypothesis proposed for this research, the statement that "semi-coke can only be produced from the Grootegeluk Mine coal source", has been partially disproved.

Other coals can provide similar performance characteristics but they may not provide the correct sulphur and phosphorus contents, or key CSR and CRI properties (arising from ranks and maceral compositions), to be acceptable to the ferroalloy industry. It is for this reason that, strategically, Exxaro's semi-coke, as produced from the Grootegeluk Coal Mine, will continue to have a major advantage over other products derived from mines so far examined in other coalfields in South Africa. It is just such factors upon which the market strategy may be built in future.

6. RECOMMENDATIONS

This report cannot be treated as an exhaustive investigation of the subject matter. It is simply a preliminary effort to demonstrate the complex nature of coal selection for a metallurgical process and the importance of fully understanding the resources available.

The outcomes of this study indicated that all the coals considered were in the vitrinite reflectance range of 0.67 – 0.69 (i.e. are in the same range of rank). It is recommended that coals outside of this reflectance range and rank be considered for further testing to determine if there are similarities.

The coals utilised in this study reported anisotropic structures when charred which is uncommon for coals from the lower ranks. Further investigations should be conducted to explore the reasons for these structures and their impact on "charring".

It is also recommended that further work be completed to better understand the relationship between the CSR and CRI of charred coals and the relationship between vitrinite content and CSR in charred coals. These relationship do not appear to conform to the expectations as cokes used in a metallurgical blast furnace application. In addition, the role of micro- and macro pore porosity must be investigated.

This study was primarily started to determine (amongst other drivers) the competitive advantage that Exxaro has in the marketplace with the production of semi-coke. Whilst this will remain of key importance to Exxaro, it is recommended that other areas also be explored. Examples of such work in the future could include the potential of producing a higher quality coke from peat hydrogenolysis instead of carbonisation. This process could potentially utilise

lower rank coals in conditions using hydrogen and carbon monoxide mixtures. The removal of oxygen to convert the non-coking coals to high quality coals with anisotropic structures should be considered. The end products could have a wider range of application than traditional “chars”.

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APPENDIX ONE (TABLES)

Exxaro Tumble Tests

Table A1-1: Tumble Tests – Sample A – D

	Sample A				Sample B				Sample C				Sample D			
	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	Mass (%) Retained on Screen	Mass retained on screen	Mass (%) Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen
Screens (mm)	Before Tumbling		After Tumbling		Before Tumbling		After Tumbling		Before Tumbling		After Tumbling		Before Tumbling		After Tumbling	
31.5	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	28.50	7.87	9.38	2.59	0.00	0.00	0.00	0.00
25	0	0.0	0.00	0.00	65.40	18.12	26.77	7.42	72.48	20.03	68.51	18.95	57.11	15.77	15.30	4.23
22.4	75.55	21.1	32.84	9.20	50.06	13.87	60.50	16.78	63.51	17.55	101.29	28.01	145.11	40.07	143.67	39.73
19	124.26	34.7	88.75	24.87	145.14	40.21	115.50	32.03	143.54	39.66	92.90	25.69	104.76	28.93	99.90	27.62
16	92.57	25.9	70.97	19.89	67.98	18.83	75.11	20.83	39.03	10.78	58.76	16.25	32.26	8.91	33.74	9.33
10	49.23	13.8	83.77	23.47	24.13	6.68	45.27	12.56	12.69	3.51	19.76	5.46	19.70	5.44	35.22	9.74
6.3	14.5	4.1	38.73	10.85	7.66	2.12	16.88	4.68	2.07	0.57	3.64	1.01	2.61	0.72	12.30	3.40
3.15	1.28	0.4	24.73	6.93	0.59	0.16	10.15	2.82	0.00	0.00	3.41	0.94	0.28	0.08	10.55	2.92
2	0.11	0.0	4.37	1.22	0.00	0.00	2.24	0.62	0.00	0.00	0.00	0.00	0.00	0.00	2.46	0.68
Pan	0.26	0.1	12.73	3.57	0.00	0.00	8.13	2.25	0.11	0.03	3.95	1.09	0.31	0.09	8.51	2.35
Total	357.76	100.0	356.89	100.00	360.96	100.00	360.55	100.00	361.93	100.00	361.6	100.00	362.14	100.00	361.65	100.00

Table A1-2: Tumble Tests – Sample E – H

	Sample E				Sample F				Sample G				Sample H			
	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen
Screens (mm)	Before Tumbling		After Tumbling		Before Tumbling		After Tumbling		Before Tumbling		After Tumbling		Before Tumbling		After Tumbling	
31.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	46.12	12.79	7.03	1.90	23.05	6.35	0.00	0.00
25	92.74	25.81	54.28	15.15	8.56	2.36	8.38	2.32	103.40	28.68	141.50	38.31	99.70	27.48	89.97	24.82
22.4	133.45	37.13	96.34	26.90	82.84	22.88	49.08	13.57	155.16	43.03	114.28	30.94	190.31	52.45	187.08	51.60
19	45.22	12.58	58.00	16.19	189.10	52.22	161.11	44.56	24.77	6.87	23.26	6.30	21.17	5.83	19.68	5.43
16	39.08	10.87	55.53	15.50	68.94	19.04	53.86	14.90	26.91	7.46	48.00	12.99	21.70	5.98	24.90	6.87
10	35.11	9.77	49.59	13.85	9.38	2.59	53.03	14.67	2.83	0.78	9.37	2.54	6.25	1.72	22.61	6.24
6.3	12.23	3.40	19.06	5.32	2.12	0.59	13.00	3.60	0.50	0.14	12.94	3.50	0.49	0.14	6.35	1.75
3.15	1.07	0.30	13.01	3.63	0.37	0.10	11.54	3.19	0.41	0.11	3.06	0.83	0.00	0.00	4.65	1.28
2	0.00	0.00	2.22	0.62	0.13	0.04	2.48	0.69	0.06	0.02	1.20	0.32	0.00	0.00	1.28	0.35
Pan	0.47	0.13	10.14	2.83	0.67	0.19	9.09	2.51	0.43	0.12	8.74	2.37	0.20	0.06	6.03	1.66
Total	359.37	100.00	358.17	100.00	362.11	100.00	361.57	100.00	360.59	100.00	369.38	100.00	362.87	100.00	362.55	100.00

Table A1-3: Tumble Tests – Exxaro Semi-Coke and Market Coke

	Exxaro Semi-Coke				Market Coke (Local)			
	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen	Mass retained on screen	% Mass Retained on Screen
Screens (mm)	Before Tumbling		After Tumbling		Before Tumbling		After Tumbling	
31.5	0.00	0.00	0.00	0.00	279.28	76.90	273.17	75.31
25	0.00	0.00	0.00	0.00	83.66	23.03	85.85	23.67
22.4	31.25	8.92	17.61	5.14	0	0.00	0	0.00
19	283.91	81.05	278.55	81.25	0	0.00	0	0.00
16	32.95	9.41	34.48	10.06	0	0.00	0	0.00
10	2.16	0.62	7.00	2.04	0	0.00	0.86	0.24
6.3	0.00	0.00	0.68	0.20	0	0.00	0.13	0.04
3.15	0.00	0.00	0.12	0.04	0	0.00	0.14	0.04
2	0.00	0.00	0.76	0.22	0	0.00	0.07	0.02
Pan	0.00	0.00	3.65	1.06	0.25	0.07	2.53	0.70
Total	350.27	100.00	342.85	100.00	363.19	100.00	362.75	100.00

Table A1-4: Charred Samples A&B – Textural Component Analysis

	SAMPLE CODES	Sample A						Sample B					
		1	2	3	4	5	6	1	2	3	4	5	6
		CARBON FORMS (Vol. %)											
	BINDER PHASE Total:	**12.3**	**47.5**	**15.6**	**31.7**	**8.6**	**15.2**	**24.7**	**5.9**	**21.3**	**7.7**	**6.4**	**50.9**
FILLER	**Organic Inerts**												
	Fine (< 50 µm)	60.5	31.8	61.1	38.2	63.0	68.8	55.5	46.7	45.8	68.1	74.6	32.9
	Coarse (> 50 µm)	26.4	19.9	17.5	25.1	26.8	12.9	19.0	45.9	31.4	22.8	18.6	14.3
	Sub-total	**86.9**	**51.7**	**78.6**	**63.3**	**89.8**	**81.7**	**74.5**	**92.6**	**77.2**	**90.9**	**93.2**	**47.2**
	Miscellaneous Inerts												
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts												
	Fine (< 50 µm)	0.4	0.8	2.3	2.7	1.2	2.7	0.4	1.1	1.1	0.7	0.4	1.9
	Coarse (50 µm)	0.4	0.0	2.3	1.9	0.4	0.4	0.0	0.0	0.4	0.0	0.0	0.0
	Pyritic Minerals	0.0	0.0	1.2	0.4	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0
	Sub-total	**0.8**	**0.8**	**5.8**	**5.0**	**1.6**	**3.1**	**0.4**	**1.5**	**1.5**	**0.7**	**0.4**	**1.9**
	FILLER PHASE Total:	**87.7**	**52.5**	**84.4**	**68.3**	**91.4**	**84.8**	**74.9**	**94.1**	**78.7**	**91.6**	**93.6**	**49.1**
MISCELLNEOUS MATERIALS	**Depositional Carbons**												
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.7	0.0	0.0
	Pyrolytic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.4**	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other												
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.4**	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-5: Charred Samples C&D – Textural Component Analysis

	SAMPLE CODES	Sample C						Sample D					
		1	2	3	4	5	6	1	2	3	4	5	6
		CARBON FORMS (Vol. %)											
	BINDER PHASE Total:	**28.0**	**51.9**	**4.1**	**21.4**	**6.9**	**6.7**	**25.4**	**42.3**	**23.5**	**33.4**	**33.2**	**39.2**
FILLER	**Organic Inerts**												
	Fine (< 50 µm)	50.2	32.3	68.2	51.2	63.0	69.0	60.1	46.7	58.8	51.6	51.5	50.3
	Coarse (> 50 µm)	18.1	15.4	27.7	24.7	29.2	22.5	13.4	10.3	16.7	13.3	14.1	9.2
	Sub-total	**68.3**	**47.7**	**95.9**	**75.9**	**92.2**	**91.5**	**73.5**	**57.0**	**75.5**	**64.9**	**65.6**	**59.5**
	Miscellaneous Inerts												
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts												
	Fine (< 50 µm)	2.7	0.4	0.0	1.0	0.3	0.7	0.8	0.5	1.0	0.2	0.5	1.0
	Coarse (50 µm)	0.7	0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	1.0	0.2	0.0
	Pyritic Minerals	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.3	0.3
	Sub-total	**3.4**	**0.4**	**0.0**	**1.3**	**0.3**	**0.7**	**1.1**	**0.7**	**1.0**	**1.5**	**1.0**	**1.3**
	FILLER PHASE Total:	**71.7**	**48.1**	**95.9**	**77.2**	**92.5**	**92.2**	**74.6**	**57.7**	**76.5**	**66.4**	**66.6**	**60.8**
MISCELLNEOUS MATERIALS	**Depositional Carbons**												
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.3	0.0	0.0	1.4	0.6	1.1	0.0	0.0	0.0	0.2	0.2	0.0
	Pyrolytic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.3**	**0.0**	**0.0**	**1.4**	**0.6**	**1.1**	**0.0**	**0.0**	**0.0**	**0.2**	**0.2**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other												
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.3**	**0.0**	**0.0**	**1.4**	**0.6**	**1.1**	**0.0**	**0.0**	**0.0**	**0.2**	**0.2**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-6 – Charred Samples E&F – Textural Component Analysis

	SAMPLE CODES	Sample E						Sample F					
		1	2	3	4	5	6	1	2	3	4	5	6
		CARBON FORMS (Vol. %)											
	BINDER PHASE Total:	**13.3**	**78.6**	**65.2**	**76.4**	**70.5**	**72.6**	**27.9**	**18.9**	**12.0**	**53.2**	**13.1**	**18.9**
FILLER	**Organic Inerts**												
	Fine (< 50 µm)	63.8	8.2	29.1	16.3	24.8	21.1	60.8	63.6	76.3	39.5	75.2	60.2
	Coarse (> 50 µm)	21.7	3.1	4.2	5.4	3.9	3.5	8.5	16.4	11.0	5.5	10.5	18.5
	Sub-total	**85.5**	**11.3**	**33.3**	**21.7**	**28.7**	**24.6**	**69.3**	**80.0**	**87.3**	**45.0**	**85.7**	**78.7**
	Miscellaneous Inerts												
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts												
	Fine (< 50 µm)	1.2	3.5	1.1	1.9	0.8	1.2	2.1	1.1	0.7	0.7	0.4	1.6
	Coarse (50 µm)	0.0	2.3	0.4	0.0	0.0	0.8	0.7	0.0	0.0	0.7	0.8	0.8
	Pyritic Minerals	0.0	4.3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.4	0.0	0.0
	Sub-total	**1.2**	**10.1**	**1.5**	**1.9**	**0.8**	**2.8**	**2.8**	**1.1**	**0.7**	**1.8**	**1.2**	**2.4**
	FILLER PHASE Total:	**86.7**	**21.4**	**34.8**	**23.6**	**29.5**	**27.4**	**72.1**	**81.1**	**88.0**	**46.8**	**86.9**	**81.1**
MISCELLNEOUS MATERIALS	**Depositional Carbons**												
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Pyrolytic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other												
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-7 – Charred Samples G&H – Textural Component Analysis

	SAMPLE CODES	Sample G						Sample H					
		1	2	3	4	5	6	1	2	3	4	5	6
		CARBON FORMS (Vol. %)											
	BINDER PHASE Total:	**22.9**	**22.8**	**13.7**	**22.2**	**10.2**	**18.7**	**33.8**	**54.1**	**17.8**	**10.5**	**32.8**	**23.8**
FILLER	**Organic Inerts**												
	Fine (< 50 µm)	61.7	59.8	76.1	60.9	76.1	67.5	54.4	36.6	68	58	39.6	58.6
	Coarse (> 50 µm)	14.2	17.4	10.2	16.5	13.3	13.1	9.6	7.2	13.8	30.8	18.2	17.2
	Sub-total	**75.9**	**77.2**	**86.3**	**77.4**	**89.4**	**80.6**	**64.0**	**43.8**	**81.8**	**88.8**	**57.8**	**75.8**
	Miscellaneous Inerts												
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts												
	Fine (< 50 µm)	1.2	0.0	0.0	0.4	0.4	0.7	1.5	1.4	0.4	0.7	3.5	0.4
	Coarse (50 µm)	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.7	0.0	0.0	5.9	0.0
	Pyritic Minerals	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**1.2**	**0.0**	**0.0**	**0.4**	**0.4**	**0.7**	**2.2**	**2.1**	**0.4**	**0.7**	**9.4**	**0.4**
	FILLER PHASE Total:	**77.1**	**77.2**	**86.3**	**77.8**	**89.8**	**81.3**	**66.2**	**45.9**	**82.2**	**89.5**	**67.2**	**76.2**
MISCELLNEOUS MATERIALS	**Depositional Carbons**												
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Pyrolytic	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other												
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-8 – Semi-Coke – Textural Component Analysis

	SAMPLE CODES	Exxaro Semi-Coke					
		1	2	3	4	5	6
		CARBON FORMS (Vol. %)					
	BINDER PHASE Total:	**14.8**	**9.6**	**20.2**	**45.0**	**23.0**	**13.4**
FILLER	**Organic Inerts**						
	Fine (< 50 µm)	57.6	61.8	52.0	43.5	64.0	76.4
	Coarse (> 50 µm)	26.8	28.6	26.7	11.5	13.0	8.0
	Sub-total	**84.4**	**90.4**	**78.7**	**55.0**	**77.0**	**84.4**
	Miscellaneous Inerts						
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts						
	Fine (< 50 µm)	0.8	0.0	0.4	0.0	0.0	2.2
	Coarse (50 µm)	0.0	0.0	0.0	0.0	0.0	0.0
	Pyritic Minerals	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.8**	**0.0**	**0.4**	**0.0**	**0.0**	**2.2**
	FILLER PHASE Total:	**85.2**	**90.4**	**79.1**	**55.0**	**77.0**	**86.6**
MISCELLNEOUS MATERIALS	**Depositional Carbons**						
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.0	0.0	0.0	0.0	0.0	0.0
	Pyrolytic	0.0	0.0	0.7	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other						
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.0**	**0.0**	**0.7**	**0.0**	**0.0**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-9 – Market Coke – Textural Component Analysis

	SAMPLE CODES	Market Coke (Local)											
		1	2	3	4	5	6	7	8	9	10	11	12
		CARBON FORMS (Vol. %)											
	BINDER PHASE Total:	**93.6**	**88.5**	**92.9**	**85.2**	**90.9**	**86.9**	**90.7**	**92.8**	**92.5**	**93.4**	**95.5**	**95.7**
FILLER	**Organic Inerts**												
	Fine (< 50 µm)	3.2	9.1	3.5	9.7	6.3	7.9	5.8	5.4	4.5	2.7	1.5	3.1
	Coarse (> 50 µm)	0.0	0.0	0.0	0.4	0.0	0.4	0.3	0	0.4	0	0	0
	Sub-total	**3.2**	**9.1**	**3.5**	**10.1**	**6.3**	**8.3**	**6.1**	**5.4**	**4.9**	**2.7**	**1.5**	**3.1**
	Miscellaneous Inerts												
	Oxidised Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Non-coking Vitrinite	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Inorganic Inerts												
	Fine (< 50 µm)	2.0	1.6	1.6	0.4	2.0	2.0	1.0	0.7	1.1	1.2	1.5	0.8
	Coarse (50 µm)	0.8	0.8	1.2	1.2	0.4	0.4	0.0	0.7	1.1	0.8	0.4	0.0
	Pyritic Minerals	0.4	0.0	0.8	0.8	0.4	2.0	0.6	0.4	0.0	0.8	0.7	0.4
	Sub-total	**3.2**	**2.4**	**3.6**	**2.4**	**2.8**	**4.4**	**1.6**	**1.8**	**2.2**	**2.8**	**2.6**	**1.2**
	FILLER PHASE Total:	**6.4**	**11.5**	**7.1**	**12.5**	**9.1**	**12.7**	**7.7**	**7.2**	**7.1**	**5.5**	**4.1**	**4.3**
MISCELLNEOUS MATERIALS	**Depositional Carbons**												
	Sooty	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Spherulitic	0.0	0.0	0.0	0.4	0.0	0.0	0.6	0.0	0.0	0.0	0.0	0.0
	Pyrolytic	0.0	0.0	0.0	1.9	0.0	0.0	1.0	0.0	0.0	1.1	0.4	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**2.3**	**0.0**	**0.0**	**1.6**	**0.0**	**0.0**	**1.1**	**0.4**	**0.0**
	Additive Carbons	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
	Other												
	Green Coke	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Coal	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Contaminating Particles	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Burnt	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.4	0.0	0.0	0.0
	Sub-total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.4**	**0.0**	**0.0**	**0.4**	**0.0**	**0.0**	**0.0**
	MISCELLANEOUS MATERIALS Total:	**0.0**	**0.0**	**0.0**	**2.3**	**0.0**	**0.4**	**1.6**	**0.0**	**0.4**	**1.1**	**0.4**	**0.0**
	TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-10 – Market Coke Historical Analysis (2015 vs. 2016) – Textural Component Analysis

	SAMPLE CODES	Market Coke (Local)	Market Coke (Local)
		2015 Sample	2016 Average
	CARBON FORMS (Vol. %)		
	BINDER PHASE Total:	**94.0**	**91.6**
FILLER	**Organic Inerts**		
	Fine (< 50 µm)	1.6	5.2
	Coarse (> 50 µm)	1.1	0.1
	Sub-total	**2.7**	**5.4**
	Miscellaneous Inerts		
	Oxidised Coal	0.0	0.0
	Non-coking Vitrinite	0.0	0.0
	Isotropic Coke as Filler	0.0	0.0
	Sub-total	**0.0**	**0.0**
	Inorganic Inerts		
	Fine (< 50 µm)	1.1	1.3
	Coarse (50 µm)	1.0	0.7
	Pyritic Minerals	0.9	0.6
	Sub-total	**3.0**	**2.6**
	FILLER PHASE Total:	**5.7**	**7.9**
MISCELLNEOUS MATERIALS	**Depositional Carbons**		
	Sooty	0.0	0.0
	Spherulitic	0.0	0.1
	Pyrolytic	0.3	0.4
	Sub-total	**0.3**	**0.5**
	Additive Carbons	**0.0**	**0.0**
	Other		
	Green Coke	0.0	0.0
	Coal	0.0	0.0
	Contaminating Particles	0.0	0.0
	Burnt	0.0	0.1
	Sub-total	**0.0**	**0.1**
	MISCELLANEOUS MATERIALS Total:	**0.3**	**0.5**
	TOTAL %	**100.0**	**100.0**

Table A1-11 – Binder Phase of Charred Samples A & B – Textural Component Analysis

SAMPLE CODES	Sample A						Sample B					
CARBON FORMS (Vol. %)	1	2	3	4	5	6	1	2	3	4	5	6
BINDER PHASE												
Isotropic (from V7 or lower)	95.7	100.0	100.0	97.3	94.9	87.3	96.8	93.8	97.6	98.0	96.7	99.1
Incipient Anistropic (from V8)	2.1	0.0	0.0	0.0	2.6	9.5	0.0	0.0	2.4	0.0	0.0	0.9
Sub-Total	**97.8**	**100.0**	**100.0**	**97.3**	**97.5**	**96.8**	**96.8**	**93.8**	**100.0**	**98.0**	**96.7**	**100.0**
Circular Anisotropic (Granular)												
Fine (From V9)	0.0	0.0	0.0	0.0	0.0	3.2	1.1	6.3	0.0	2.0	0.0	0.0
0.5 - 1.0 µm												
Medium (from V10)	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.0 - 1.5 µm												
Coarse (From V11)	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0
1.5 - 2.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**1.4**	**0.0**	**3.2**	**2.2**	**6.3**	**0.0**	**2.0**	**0.0**	**0.0**
Lenticular (Leaflet) Anisotropic												
Fine (From V12)	2.1	0	0	0	2.6	0	1.1	0	0	0	3.3	0
width 1.0 - 3.0 µm												
Medium (from V13)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
width 3.0 - 8.0 µm												
Coarse (From V14)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 8.0 - 12.0 µm												
Sub-Total	**2.10**	**0.00**	**0.00**	**0.00**	**2.60**	**0.00**	**1.10**	**0.00**	**0.00**	**0.00**	**3.30**	**0.00**
Ribbon (Flow) Anisotropic												
Fine (From V15)	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 2.0 - 12.0 µm												
Medium (from V16)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 12.0 - 36.0 µm												
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**1.4**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-12 – Binder Phase of Charred Samples C & D – Textural Component Analysis

SAMPLE CODES	Sample C						Sample D					
CARBON FORMS (Vol. %)	1	2	3	4	5	6	1	2	3	4	5	6
BINDER PHASE												
Isotropic (from V7 or lower)	37.7	96.9	56.7	19.8	32.4	47.7	94.8	96.3	97.0	100.0	98.4	99.4
Incipient Anistropic (from V8)	1.9	0.8	13.3	8.9	11.8	2.3	2.4	0.7	2.1	0.0	0.8	0.6
Sub-Total	**39.6**	**97.7**	**70.0**	**28.7**	**44.2**	**50.0**	**97.2**	**97.0**	**99.1**	**100.0**	**99.2**	**100.0**
Circular Anisotropic (Granular)												
Fine (From V9)	9.1	0.8	10.0	22.8	11.8	20.5	1.4	0.4	1.0	0.0	0.0	0.8
0.5 - 1.0 µm												
Medium (from V10)	4.5	0.0	3.3	5.0	2.9	4.5	0.5	0.7	0.0	0.0	0.0	0.0
1.0 - 1.5 µm												
Coarse (From V11)	9.1	0.0	3.3	9.9	5.9	9.1	0.0	0.7	0.0	0.0	0.0	0.0
1.5 - 2.0 µm												
Sub-Total	**22.7**	**0.8**	**16.6**	**37.7**	**20.6**	**34.1**	**1.9**	**1.8**	**1.0**	**0.0**	**0.0**	**0.8**
Lenticular (Leaflet) Anisotropic												
Fine (From V12)	20.8	0.8	10.0	21.8	20.6	11.4	0.9	1.1	0.0	0.0	0.0	0.0
width 1.0 - 3.0 µm												
Medium (from V13)	6.5	0.8	3.3	3.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0
width 3.0 - 8.0 µm												
Coarse (From V14)	3.2	0.0	0.0	0.0	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 8.0 - 12.0 µm												
Sub-Total	**30.5**	**1.6**	**13.3**	**24.8**	**23.5**	**15.9**	**0.9**	**1.1**	**0.0**	**0.0**	**0.0**	**0.0**
Ribbon (Flow) Anisotropic												
Fine (From V15)	7.1	0.0	0.0	7.9	8.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 2.0 - 12.0 µm												
Medium (from V16)	0.0	0.0	0.0	1.1	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 12.0 - 36.0 µm												
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm												
Sub-Total	**7.1**	**0.0**	**0.0**	**9.0**	**11.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-13 – Binder Phase of Charred Samples E & F – Textural Component Analysis

SAMPLE CODES	Sample E						Sample F					
CARBON FORMS (Vol. %)	1	2	3	4	5	6	1	2	3	4	5	6
BINDER PHASE												
Isotropic (from V7 or lower)	98.7	100.0	99.1	99.4	99.4	100.0	93.8	100.0	100.0	100.0	96.7	92.6
Incipient Anistropic (from V8)	1.3	0.0	0.9	0.6	0.6	0.0	4.5	0.0	0.0	0.0	1.6	4.1
Sub-Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**98.3**	**100.0**	**100.0**	**100.0**	**98.3**	**96.7**
Circular Anisotropic (Granular)												
Fine (From V9)	0.0	0.0	0.0	0.0	0.0	0.0	1.8	0.0	0.0	0.0	1.6	2.5
0.5 - 1.0 µm												
Medium (from V10)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
1.0 - 1.5 µm												
Coarse (From V11)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1.5 - 2.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**1.8**	**0.0**	**0.0**	**0.0**	**1.6**	**3.3**
Lenticular (Leaflet) Anisotropic												
Fine (From V12)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 1.0 - 3.0 µm												
Medium (from V13)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 3.0 - 8.0 µm												
Coarse (From V14)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 8.0 - 12.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
Ribbon (Flow) Anisotropic												
Fine (From V15)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 2.0 - 12.0 µm												
Medium (from V16)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 12.0 - 36.0 µm												
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-14 – Binder Phase of Charred Samples G & H – Textural Component Analysis

SAMPLE CODES	Sample G						Sample H					
CARBON FORMS (Vol. %)	1	2	3	4	5	6	1	2	3	4	5	6
BINDER PHASE												
Isotropic (from V7 or lower)	99.1	88.5	94.0	60.7	74.4	90.1	94.0	98.1	90.0	93.7	100.0	100.0
Incipient Anistropic (from V8)	0.9	5.8	4.0	11.9	3.7	4.1	0.9	0.0	2.0	0.0	0.0	0.0
Sub-Total	**100.0**	**94.3**	**98.0**	**72.6**	**78.1**	**94.2**	**94.9**	**98.1**	**92.0**	**93.7**	**100.0**	**100.0**
Circular Anisotropic (Granular)												
Fine (From V9)	0.0	4.3	2.0	10.7	4.9	2.5	0.9	0.0	2.0	1.3	0.0	0.0
0.5 - 1.0 µm												
Medium (from V10)	0.0	0.7	0.0	6.0	3.7	0.8	0.9	0.0	2.0	0.0	0.0	0.0
1.0 - 1.5 µm												
Coarse (From V11)	0.0	0.7	0.0	3.6	1.2	0.0	0.9	0.0	0.0	1.3	0.0	0.0
1.5 - 2.0 µm												
Sub-Total	**0.0**	**5.7**	**2.0**	**20.3**	**9.8**	**3.3**	**2.7**	**0.0**	**4.0**	**2.6**	**0.0**	**0.0**
Lenticular (Leaflet) Anisotropic												
Fine (From V12)	0.0	0.0	0.0	1.2	4.9	1.7	1.7	1.3	4.0	3.8	0.0	0.0
width 1.0 - 3.0 µm												
Medium (from V13)	0.0	0.0	0.0	6.0	6.1	0.8	0.9	0.6	0.0	0.0	0.0	0.0
width 3.0 - 8.0 µm												
Coarse (From V14)	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 8.0 - 12.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**7.2**	**12.2**	**2.5**	**2.6**	**1.9**	**4.0**	**3.8**	**0.0**	**0.0**
Ribbon (Flow) Anisotropic												
Fine (From V15)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 2.0 - 12.0 µm												
Medium (from V16)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 12.0 - 36.0 µm												
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm												
Sub-Total	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-15 – Binder Phase of Semi-Coke – Textural Component Analysis

SAMPLE CODES	Exxaro Semi-Coke					
CARBON FORMS (Vol. %)	1	2	3	4	5	6
BINDER PHASE						
Isotropic (from V7 or lower)	36.5	89.0	23.1	55.8	95.5	96.7
Incipient Anistropic (from V8)	14.8	2.7	13.5	3.8	2.2	2.7
Sub-Total	**51.3**	**91.7**	**36.6**	**59.6**	**97.7**	**99.4**
Circular Anisotropic (Granular)						
Fine (From V9)	9.5	2.7	23.1	11.5	1.5	0.5
0.5 - 1.0 µm						
Medium (from V10)	0.0	0.0	11.5	0.0	0.7	0.0
1.0 - 1.5 µm						
Coarse (From V11)	1.4	0.0	5.8	5.8	0.0	0.0
1.5 - 2.0 µm						
Sub-Total	**10.9**	**2.7**	**40.4**	**17.3**	**2.2**	**0.5**
Lenticular (Leaflet) Anisotropic						
Fine (From V12)	16.1	1.4	9.6	9.6	0.0	0.0
width 1.0 - 3.0 µm						
Medium (from V13)	9.5	1.4	3.8	7.7	0.0	0.0
width 3.0 - 8.0 µm						
Coarse (From V14)	6.8	0.0	0.0	1.9	0.0	0.0
width 8.0 - 12.0 µm						
Sub-Total	**32.4**	**2.8**	**13.4**	**19.2**	**0.0**	**0.0**
Ribbon (Flow) Anisotropic						
Fine (From V15)	5.4	2.7	5.8	3.8	0.0	0.0
length 2.0 - 12.0 µm						
Medium (from V16)	0.0	0.0	3.8	0.0	0.0	0.0
length 12.0 - 36.0 µm						
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm						
Sub-Total	**5.4**	**2.7**	**9.6**	**3.8**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Table A1-16 – Binder Phase of Market Coke – Textural Component Analysis

SAMPLE CODES	Market Coke (Local)											
CARBON FORMS (Vol. %)	1	2	3	4	5	6	7	8	9	10	11	12
BINDER PHASE												
Isotropic (from V7 or lower)	90.6	99.2	100.0	100.0	98.4	100.0	97.3	100.0	98.7	100.0	96.8	100.0
Incipient Anistropic (from V8)	0.8	0.8	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.4	0.0
Sub-Total	**91.4**	**100.0**	**100.0**	**100.0**	**98.4**	**100.0**	**98.4**	**100.0**	**98.7**	**100.0**	**97.2**	**100.0**
Circular Anisotropic (Granular)												
Fine (From V9)	3.4	0.0	0.0	0.0	1.6	0.0	0.5	0.0	0.4	0.0	1.2	0.0
0.5 - 1.0 µm												
Medium (from V10)	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0
1.0 - 1.5 µm												
Coarse (From V11)	0.8	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.4	0.0	0.4	0.0
1.5 - 2.0 µm												
Sub-Total	**5.3**	**0.0**	**0.0**	**0.0**	**1.6**	**0.0**	**1.0**	**0.0**	**0.8**	**0.0**	**2.0**	**0.0**
Lenticular (Leaflet) Anisotropic												
Fine (From V12)	1.9	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.8	0.0
width 1.0 - 3.0 µm												
Medium (from V13)	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0
width 3.0 - 8.0 µm												
Coarse (From V14)	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
width 8.0 - 12.0 µm												
Sub-Total	**3.1**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.5**	**0.0**	**0.4**	**0.0**	**0.8**	**0.0**
Ribbon (Flow) Anisotropic												
Fine (From V15)	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 2.0 - 12.0 µm												
Medium (from V16)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length 12.0 - 36.0 µm												
Coarse (From V17)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
length >25.0 µm												
Sub-Total	**0.4**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
TOTAL %	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

APPENDIX TWO (FIGURES)

Sample A

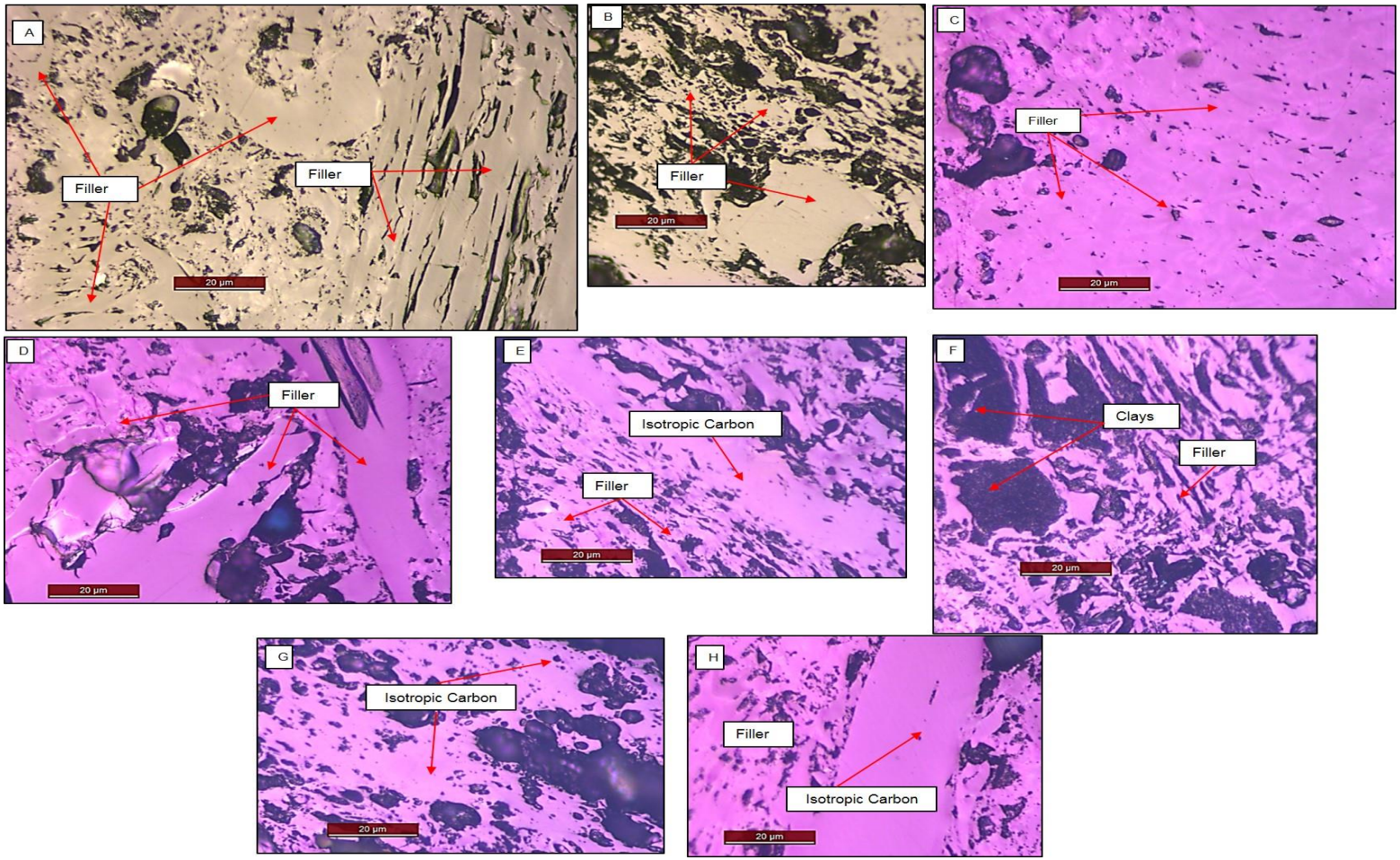

Figure A2-1: Photomicrographs of Sample A
(A, B) Plane polarised light. (C, D, E, F, G, H) Polarised light, with lambda plate inserted

Sample B

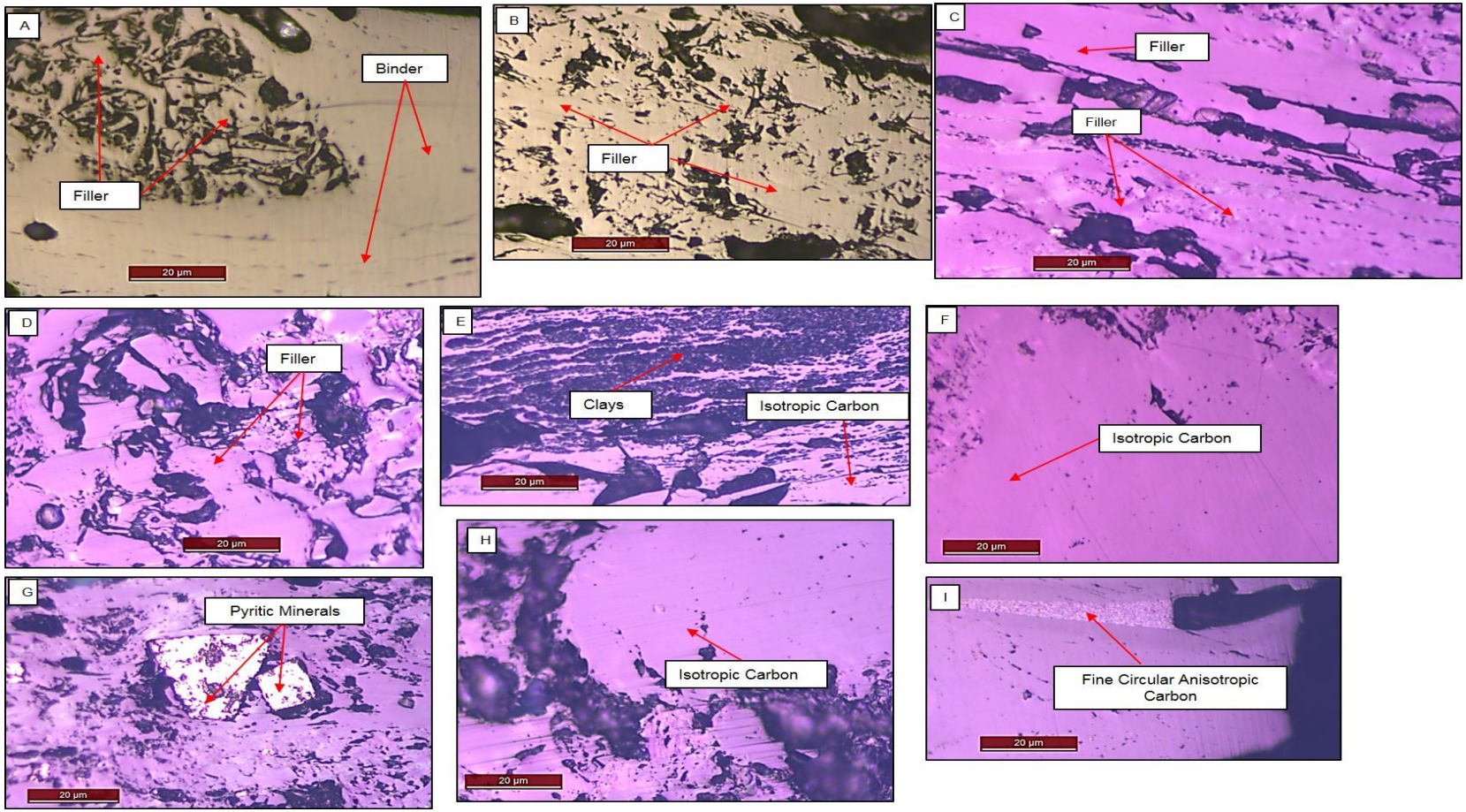

Figure A2-2: Photomicrographs of Sample B
(A, B) Plane polarised light. (C, D, E, F, G, H, I) Polarised light, with lambda plate inserted

Sample C

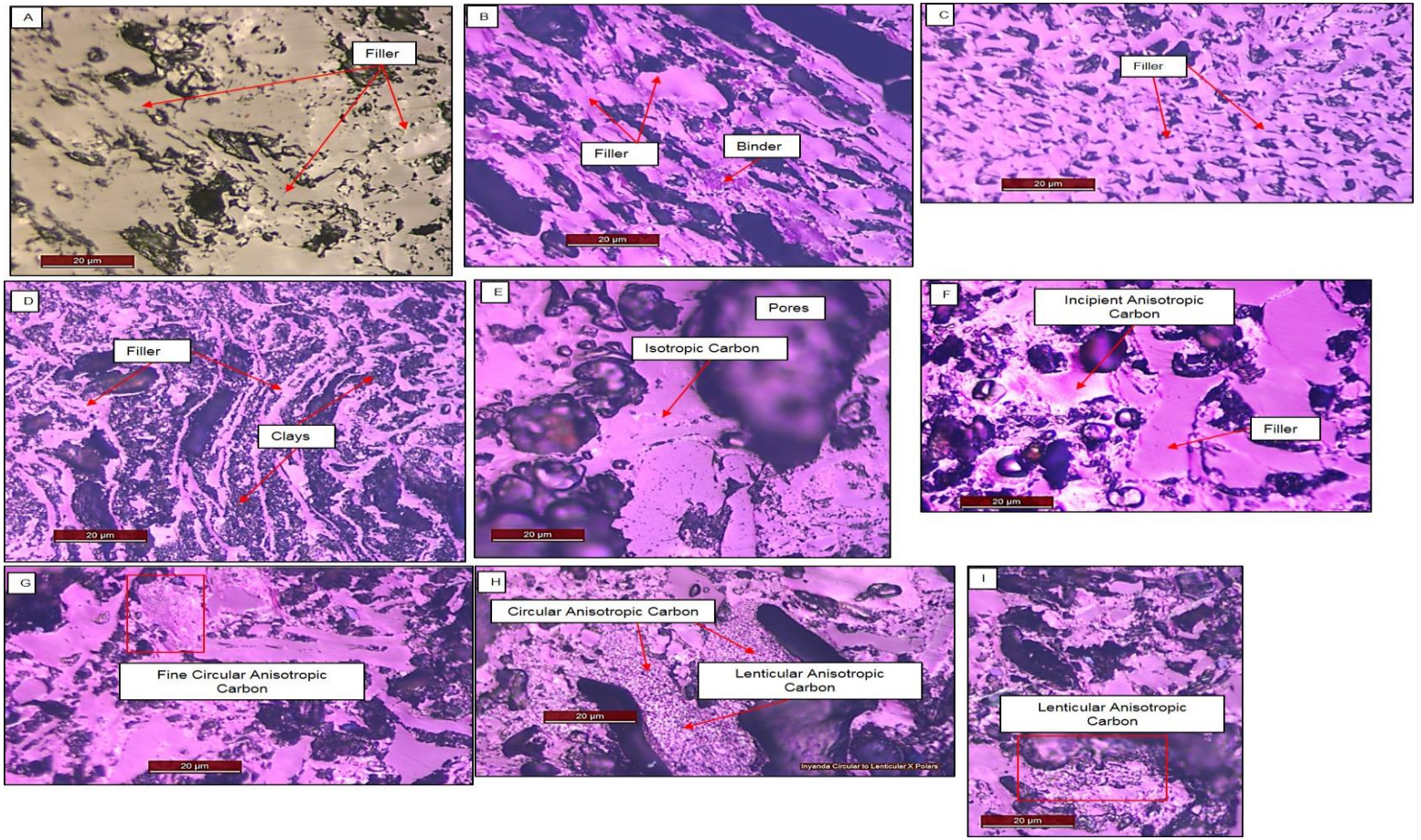

Figure A2-3: Photomicrographs of Sample C
(A) Plane polarised light. (B, C, D, E, F, G, H, I) Polarised light, with lambda plate inserted

Sample D

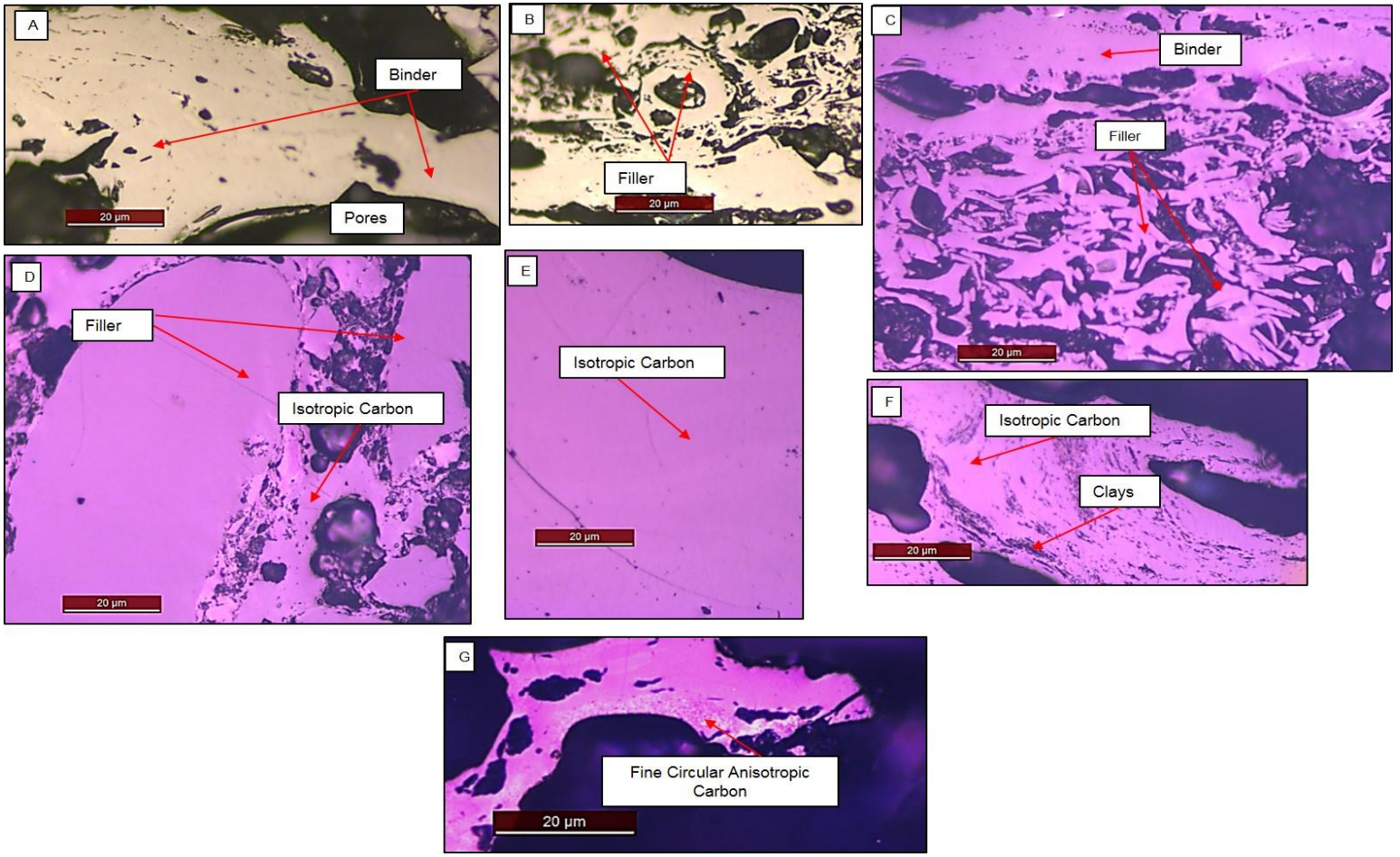

Figure A2-4: Photomicrographs of Sample D
(A, B) Plane polarised light. (C, D, E, F, G, H, I) Polarised light, with lambda plate inserted

Sample E

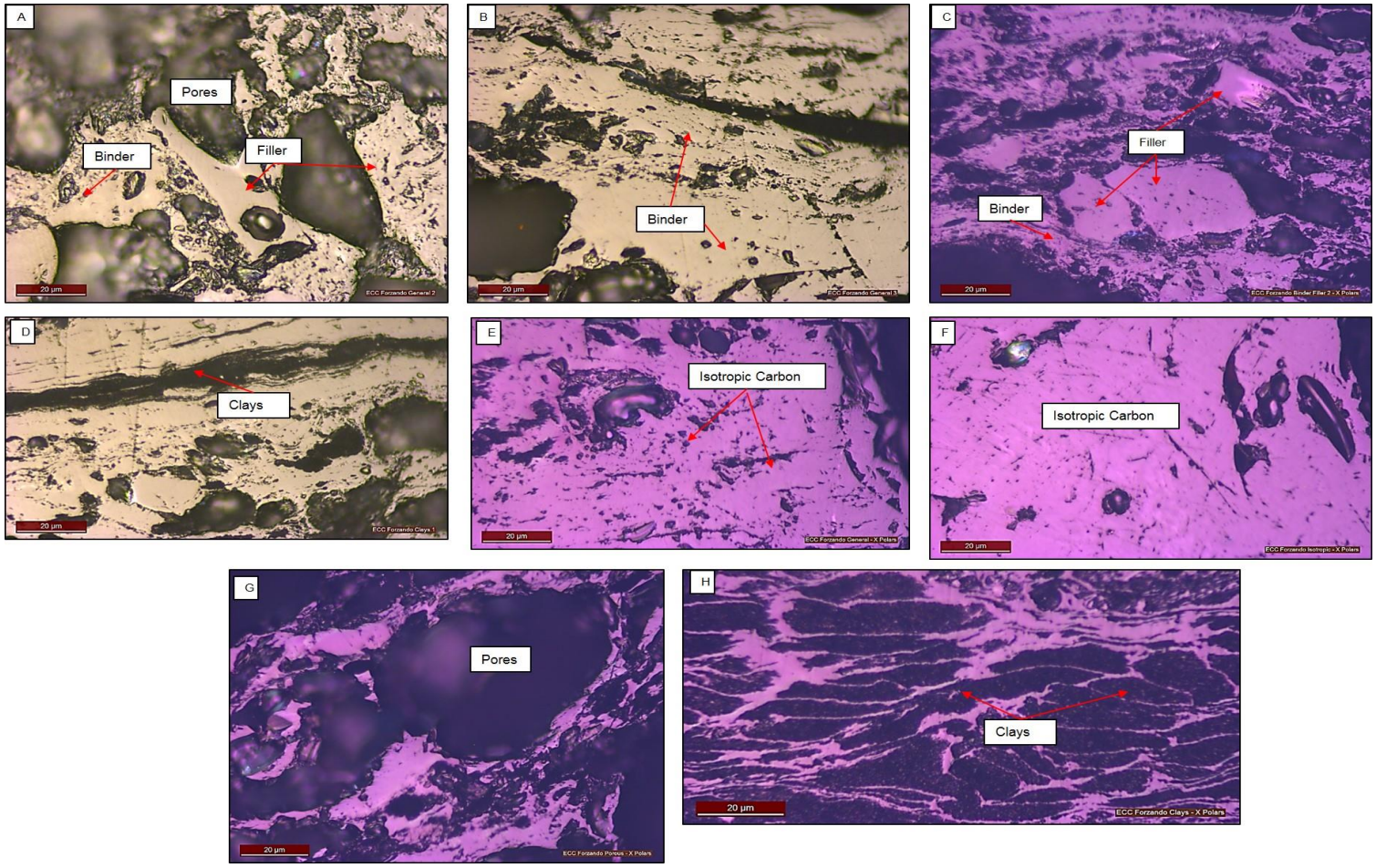

Figure A2-5: Photomicrographs of Sample E
(A, B, D) Plane polarised light. (C, E, F, G, H) Polarised light, with lambda plate inserted

Sample G

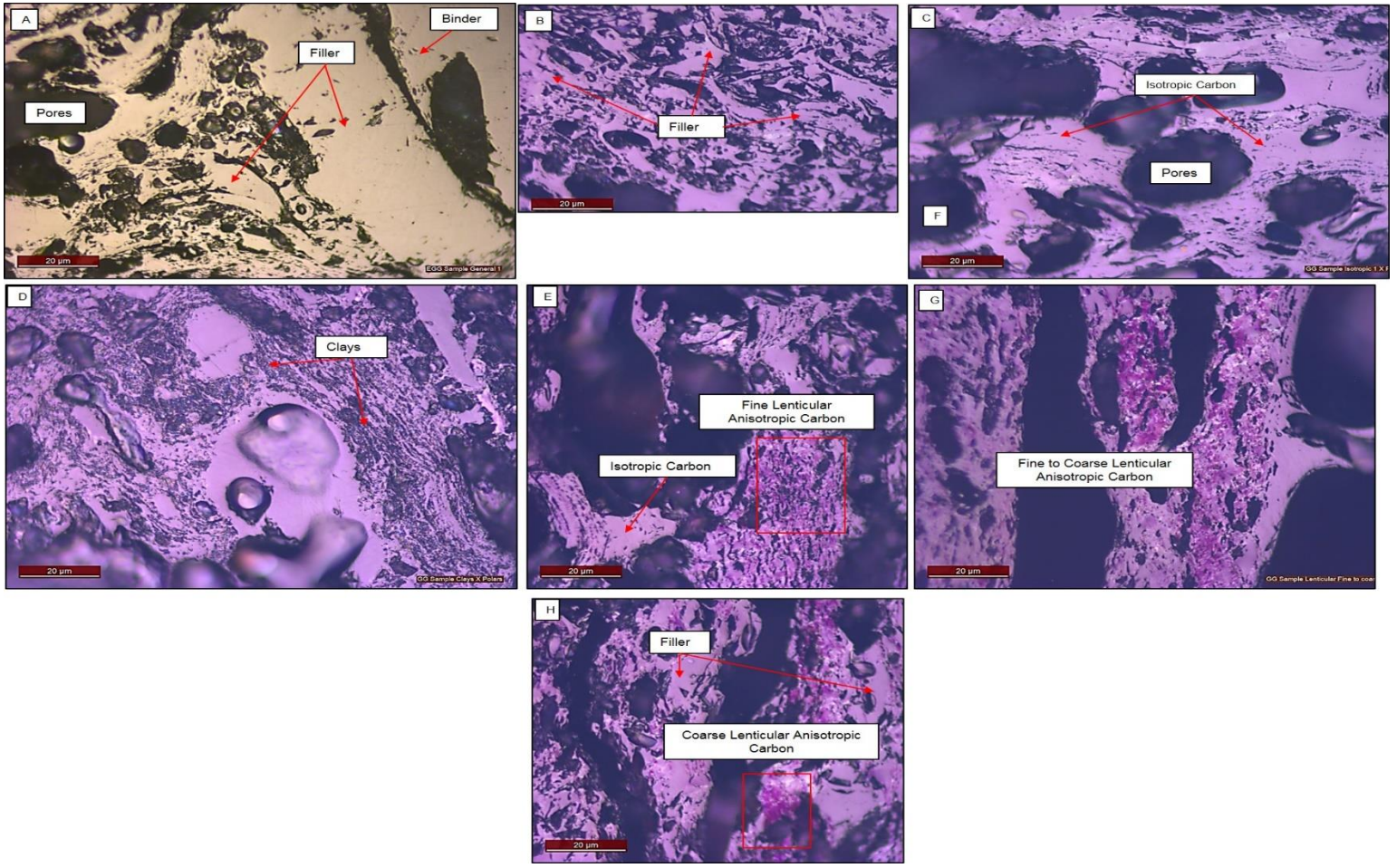

Figure A2-7: Photomicrographs of Sample G
(A) Plane polarised light. (B, C, D, E, F, G, H) Polarised light, with lambda plate inserted

Sample H

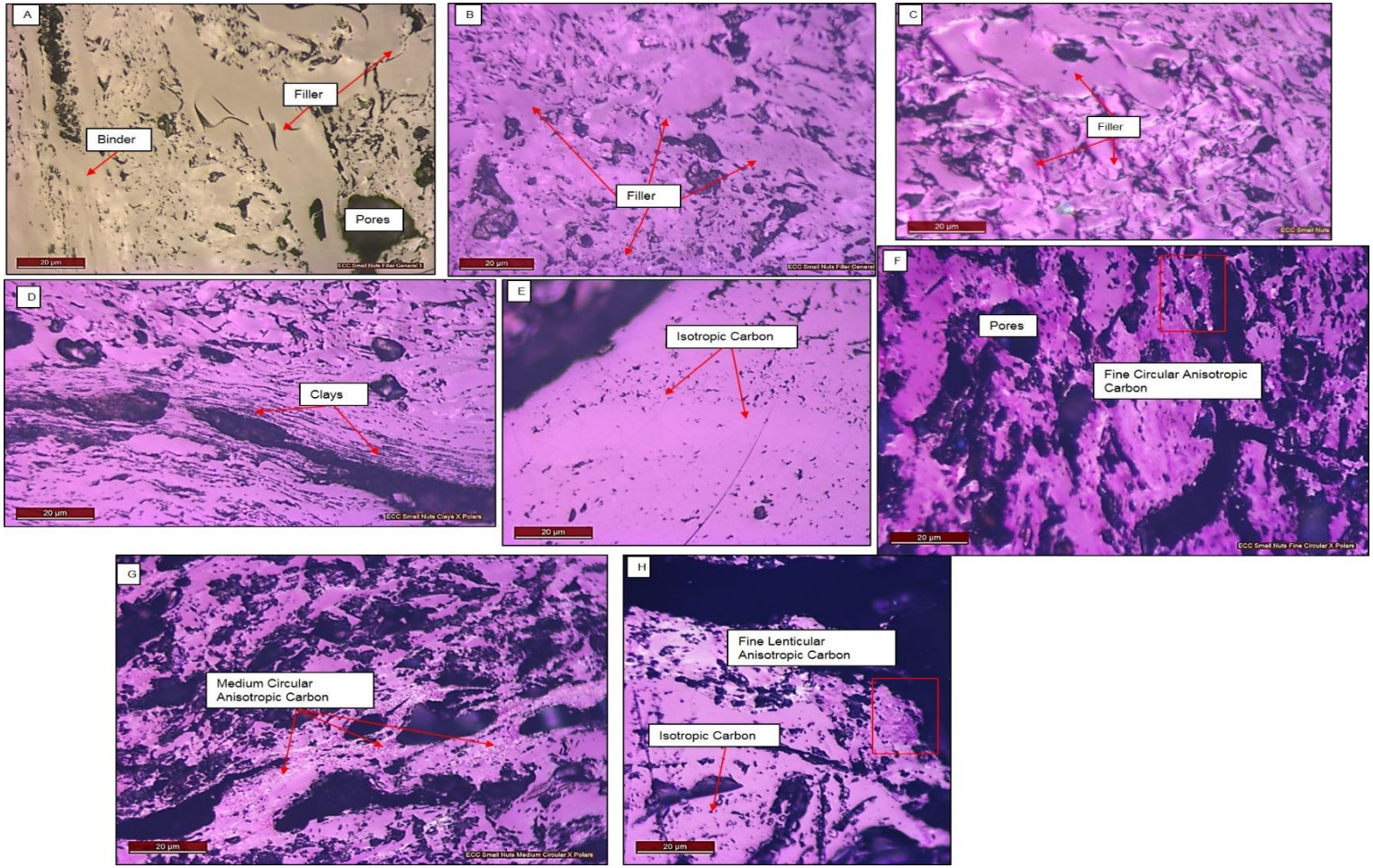

Figure A2-8: Photomicrographs of Sample H
(A) Plane polarised light. (B, C, D, E, F, G, H) Polarised light, with lambda plate inserted

Exxaro Semi-Coke

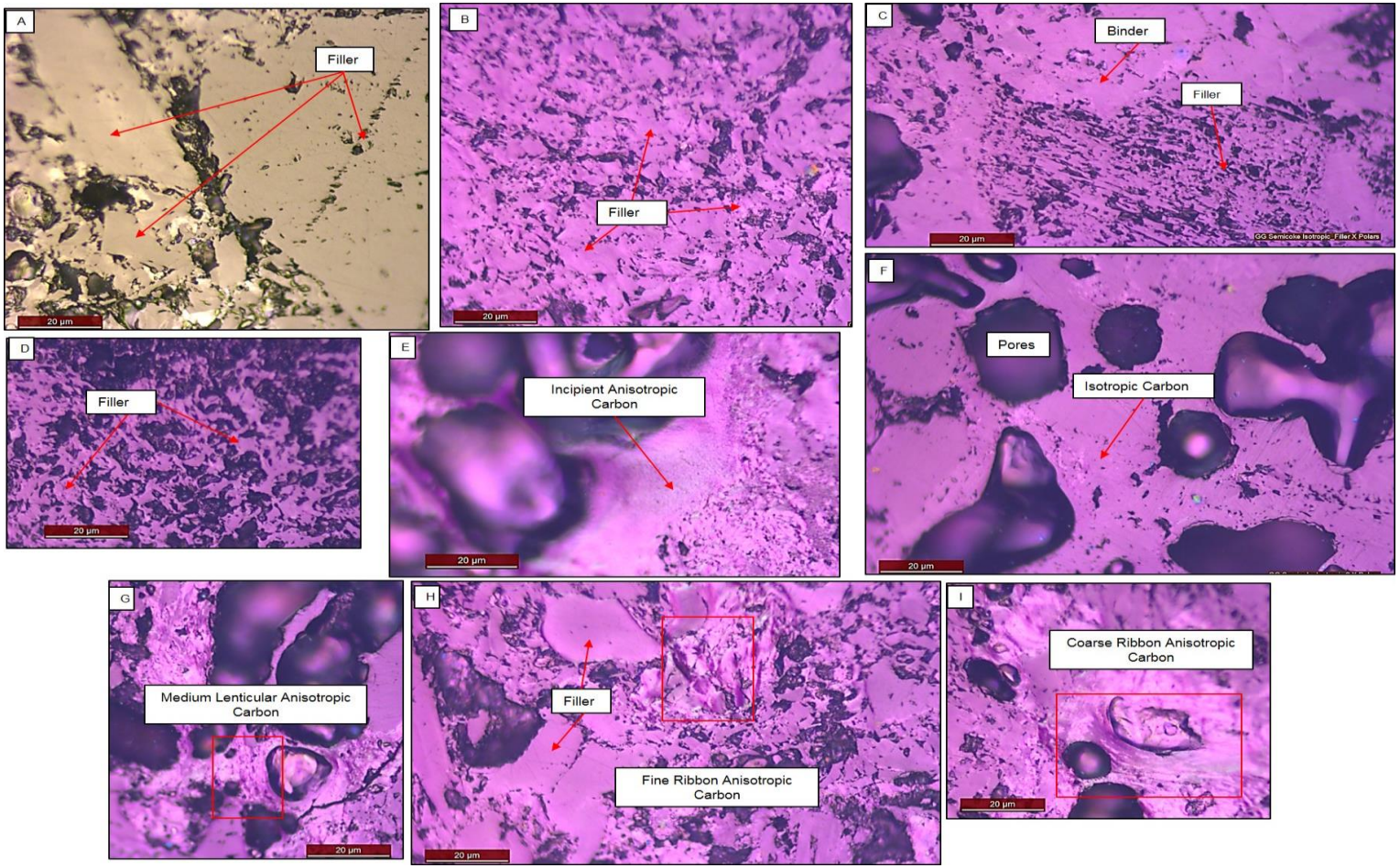

Figure A2-9: Photomicrographs of Exxaro Semi-Coke
(A) Plane polarised light. (B, C, D, E, F, G, H, I) Polarised light, with lambda plate inserted

Market Coke (Local)

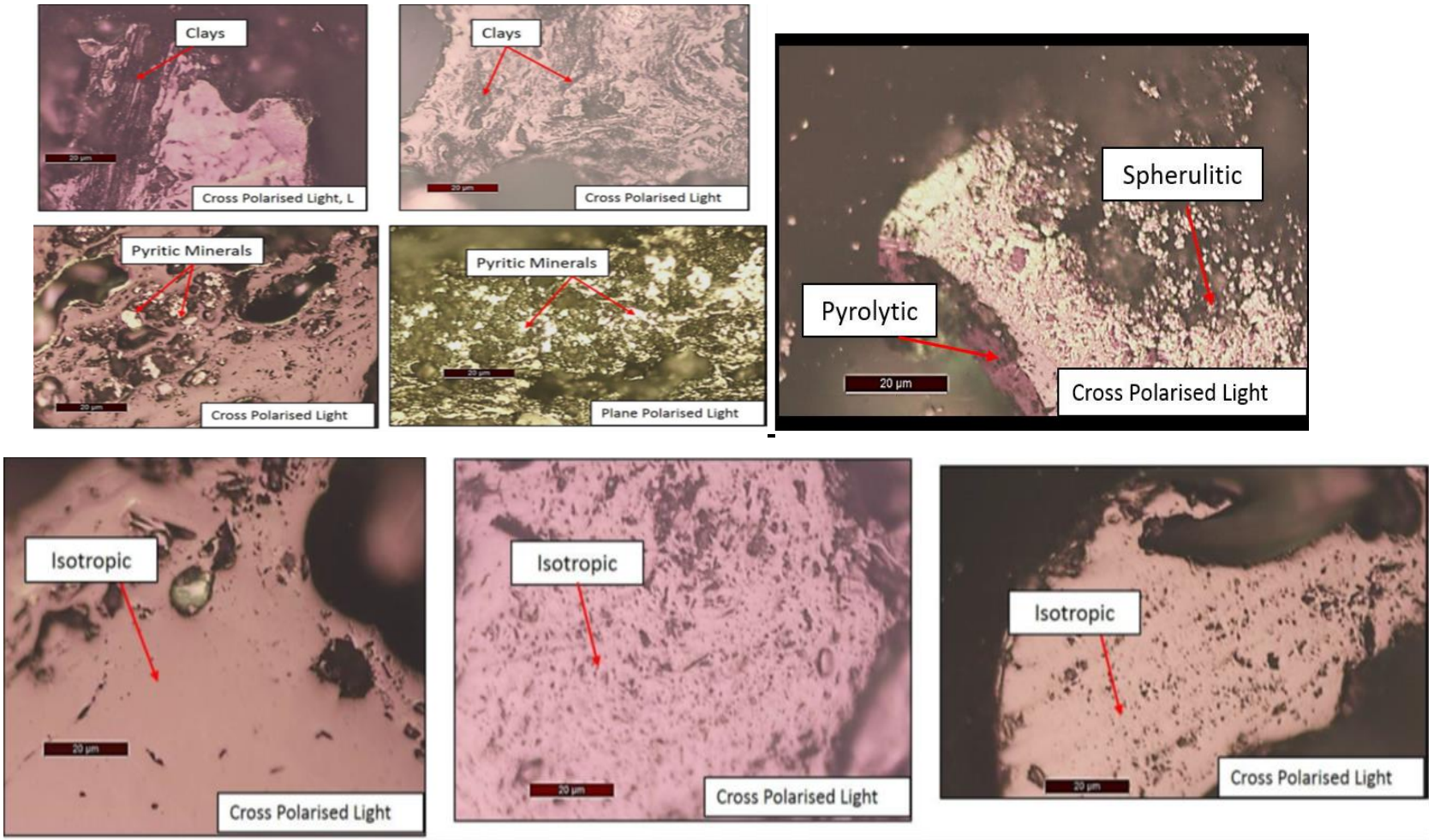

Figure A2-10: Photomicrographs of Market Coke (Local)

Isotropic / Anisotropic Relationships

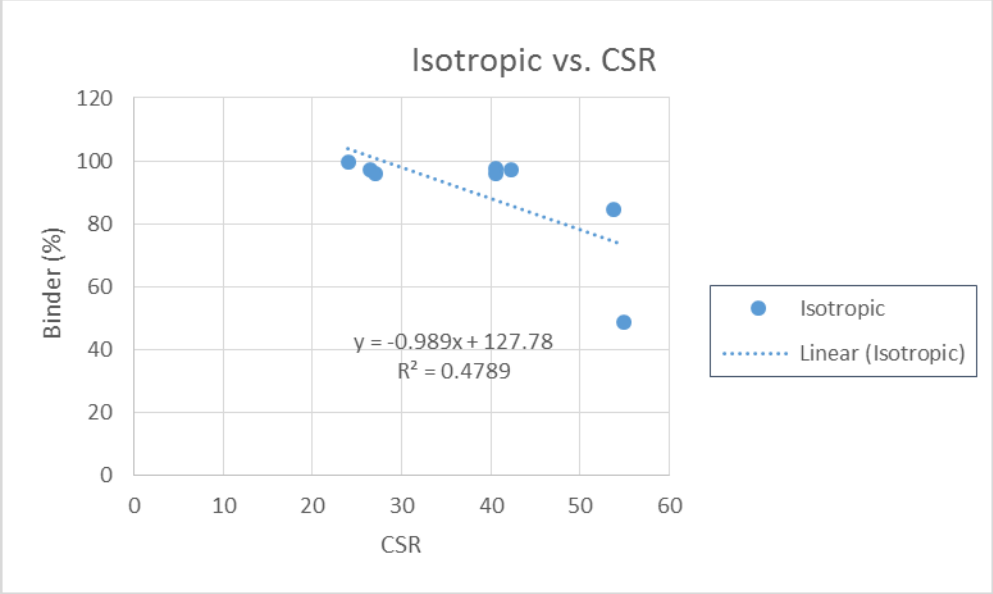

Figure A2-11: Isotropic vs. CSR

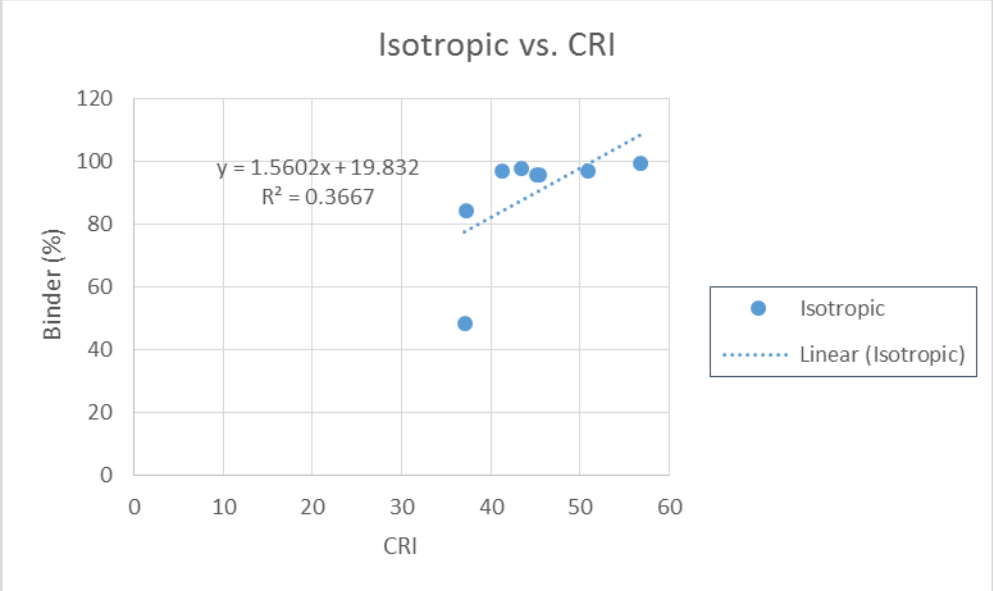

Figure A2-12: Isotropic vs. CRI

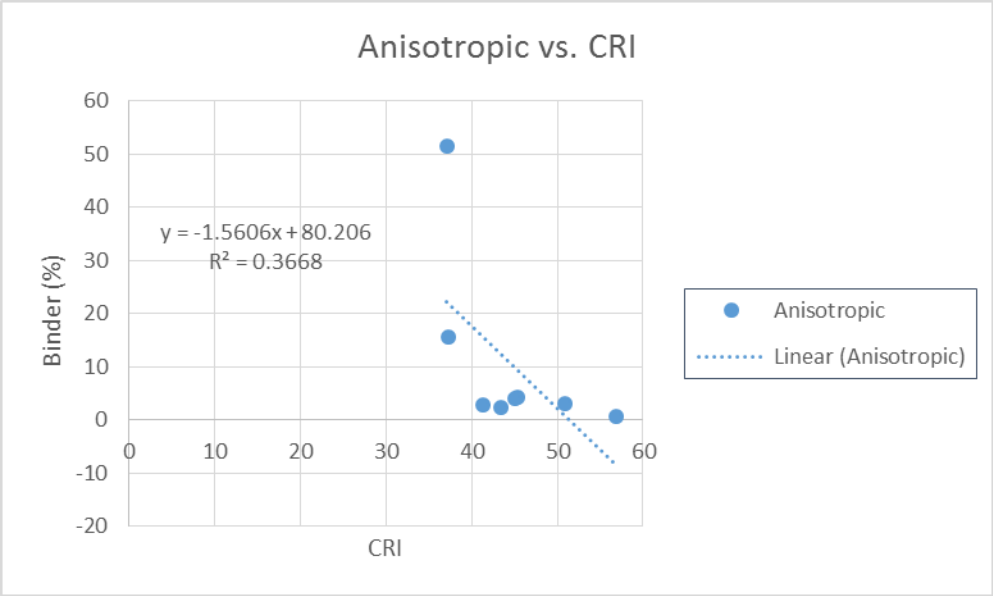

Figure A2-13: Anisotropic vs. CRI

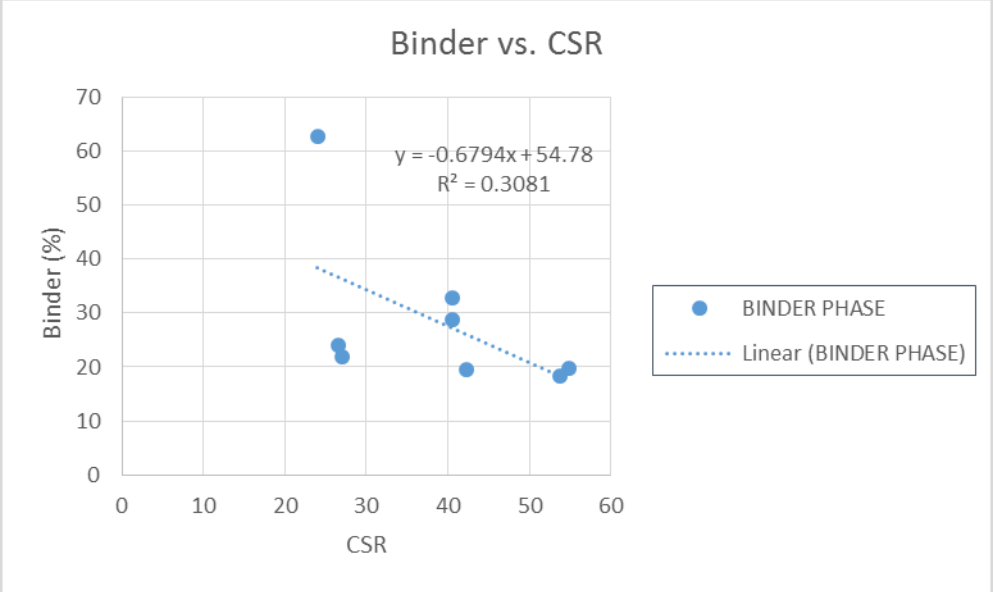

Figure A2-14: Binder vs. CSR

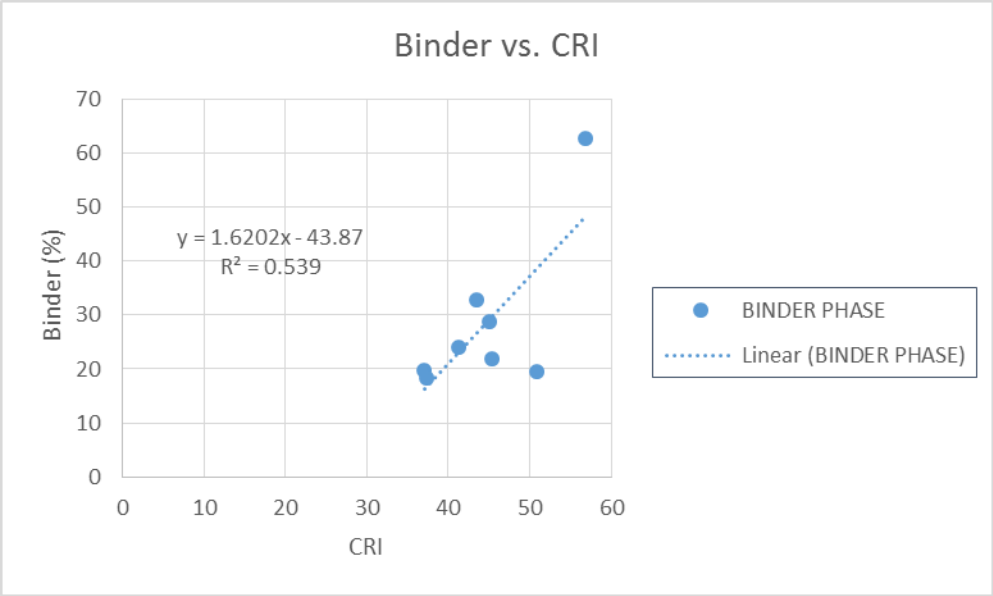

Figure A2-15: Binder vs. CRI

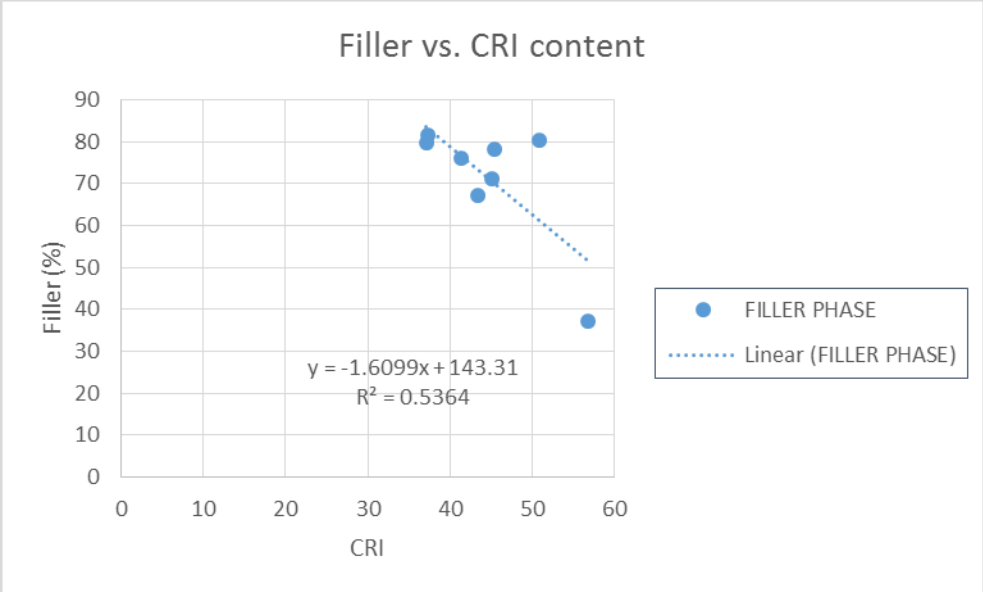

Figure A2-15: Filler vs. CRI