MOZAMBIQUE COAL - THE UNCOMMON PETROGRAPHIC QUALITY AND ITS CONSEQUENCES ON THE COKE STRENGTH[1]

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Abstract

An ideal coal blend coke must have an appropriate maceral composition (vitrinites, exinite and inertite) to provide the right balance of fusible and non-fusible material. The coal must also be in a particular range of carbonization degree or rank. This is because these parameters are directly related to the structure and texture of coke, which will determine its strength. Sources of non-fusible material are readily available, commonly from high inertinite or weakly caking coals or even petroleum coke. Sources of fusible material however are scarcer, being limited to vitrinites and exinite in coals of coking rank. High vitrinites coals from Mozambique provide an opportunity to achieve an appropriate maceral composition to optimize coke quality. The amount of vitrinites in a coal has a strong connection with the genesis and formation of deposits. The coals formed during the Carboniferous period in Europe and Eastern USA has high content of vitrinites. On the other hand, the coals formed during the Permian period in Australian and Eastern Canada have low volumes of vitrinites that may be less than 50%. The coals deposits located in the Tete Province of Mozambique in Africa, though formed in the Permian period, have high volumes of vitrinite, above 80%. This work aims to compare the results of coke resistance between coals of different origins and therefore with different levels of vitrinite content. The cokes are produced from a 40kg pilot scale oven of a renowned research center in China, and physical testing performed by the same research centre. The results indicate that high vitrinite content can positively affect both the hot and cold strength. Mozambique coals, with the highest vitrinite content in this study, achieved the best results overall in comparison to the other studied coals.

Keywords: High vitrinite; Coke quality; Cold strength; Reactivity; Hot strength.

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1 INTRODUCTION

The coal mine of VALE in Moatize, Mozambique, started production of hard coking coals in late 2011. Table 1 shows some information about the project, its reserves and planned production capacity.

Table 1. General data of Moatize I project. Annual coal production targets for 2015

Question	Answer
Coal Reserve	955 million tons (adb)
Concession time	35 years
Average mine ROM	26 Mtpy
Annual coal production	11 Mtpy
Products	Coking Coal 8.5 mtpy Thermal Coal 2.5 mtpy
Mining method	Strip mining
Budget ramp-up period	2.5 years
Faster ramp-up	1.5 years

The genesis of Moatize coal deposits had occurred in Gondwana region in the Early Permian Period (about 260 to 270 million years ago), in similar age and environmental conditions of the Australian deposits. But, the characteristics of the original organic matter and the geophysical process drove the Moatize coal formation to have better maceral characteristics in terms of vitrinite content (that comes mainly from woody tissue of trees). The Figure 1 shows the vitrinite content of current Moatize hard coking coals, some well-known global coals, as well as the coals tested in this study.

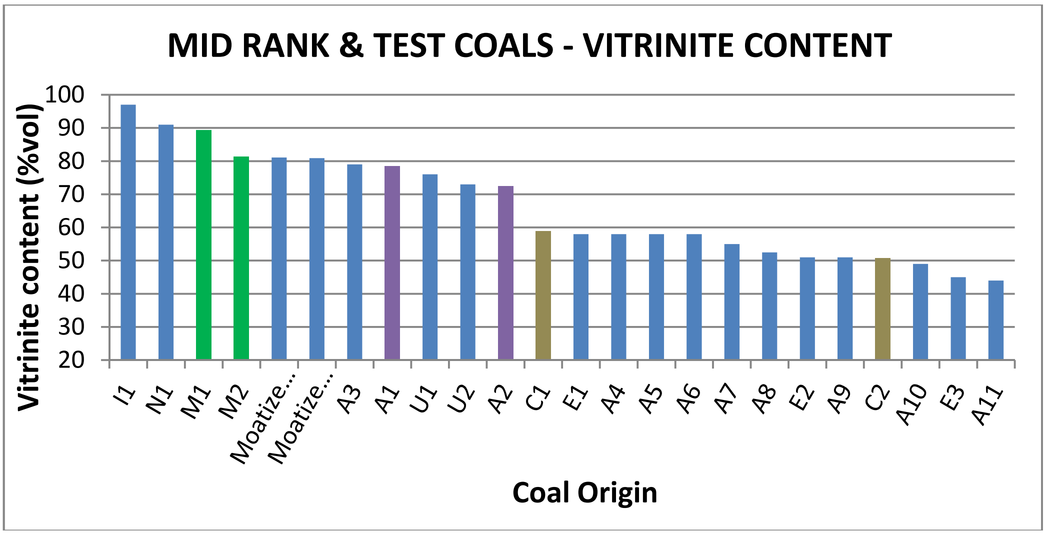

Figure 1. Vitrinite content of traditional middle rank coals, Moatize coals, and the test coals Legend: A (Australian); U (USA); E (Canadian); M (Mozambique); I (Indonesia); N (New Zealand); C (China).

Figure 2 shows, in the schematic way, the relationship between the main characteristics of coals: Macerals Reactives (fusible content – vitrinite and exinite); Vitrinite Reflectance (rank); and Max Fluidity (rheological parameter) with coke strength parameters (cold or hot) and which kind of coke characteristic could be affected (structure and/or texture).

Figure 2. Relationships between coal quality characteristics and coke resistance – cold and hot.

A higher content of vitrinite implies a lower content of inerts into the maceral composition of the coals. In case of cold resistance, inerts act as nucleator and propagator of cracks during solidification and semi-coke contraction, which makes the coke structure less compact and less resistant to degradation. With regards to hot resistance, inerts generate textures with higher isotropy level, such as fragmented and fusite, which have high reactivity to CO_2 and hence lower strength after reaction. However, having too few inerts can also have negative impacts on strength. At very high vitrinite levels there is not enough inert material to help thicken the coke pore walls and hence coke strength can deteriorate.

Vale has made efforts to understand better the Moatize coal behavior in traditional blends of the various steel mills and markets around the world. In order to obtain reliable results, VALE contracts reliable research centers and laboratories around the world. In China, the Department of Coking Technology and Quality Inspection (DCTQI) of CCRI, in Beijing, was one of the laboratories chosen for full characterization of Moatize coals.

The aim of this work is to compare the performance of examples of Moatize coals to Australian premium and Chinese coals using CCRI's cokemaking procedures and analysis. The petrography parameters of the different coals were correlated with the results of cold and hot strength obtained for the cokes.

2 METHODOLOGY

The coals used in this work were selected with different maceral contents and ranks. They were from Mozambique (M1 and M2), Australia (A1 and A2) and low rank Chinese Coals (C1 and C2). The Mozambique coals were selected to cover the range of vitrinite content available from the Moatize mine. The characterization of the samples was performed in the Department of Coking Technology and Quality Inspection (DCTQI) of CCRI, Beijing in China.

In the coal samples, the rank was determined by vitrinite reflectance measurement (GB/T 6948-2008). The petrographic composition was determined by maceral analysis using standardized procedures (GB/T 15590-2008).

The coals were charged into a pilot coke oven of 40 kg. The parameters used in the carbonization tests are shown in Table 2.

Table 2. Coking Parameters

Particle <3 mm (%)	Density (wet) t/m3	Moisture (%)	Coking time (h)	Coke Charge Center Temperature (°C)	Charging manner
82.0	0,75	8,5	18	900	Top Charging

The coke produced was analyzed for cold and hot mechanical strength. The cold mechanical strength index analyzed in the coke samples was MICUM (GB 2006-1980). The hot mechanical strength of the cokes samples have been tested according to the standardized CSR/CRI test (GB 4000-1983).

3 RESULTS AND DISCUSSION

3.1 Coal Petrography Analysis

Coals macerals and the rank values based on the reflectance measurements of the vitrinite (Rmm) are provided in Table 3. Figure 3 shows more clearly the variation of vitrinite content for the different coals analyzed.

The Rmm for the Mozambican coals was determined as 1.06% and 1.11% respectively indicating them as medium volatile bituminous coal rank. The Australian coals according the Rmm results are also classified as medium volatile bituminous coal rank. On the other hand, Chinese coals are classified as high volatile bituminous coal rank. Due to automatic measuring, the Rmm values are lower than expected. But there is consistency in the measurements across the coals allowing comparisons to be made fairly.

Table 3. Petrographic analysis, vitrinite reflectance of the coals and coke quality

Coal	Petrographic Analysis (% Vol)					
	Vitrinite	Inertinite	Semi Inertinite	Exinite	MM	R_{mm}
M1	89.4	2.8	4.3	0.0	3.5	1.06
M2	81.4	4.5	8.5	0.0	5.6	1.11
A1	78.4	4.4	13.5	0.0	3.7	1.28
A2	72.3	4.3	18.2	0.0	4.9	1.20
C1	58.9	6.7	19.7	10.0	4.7	0.73
C2	50.7	3.4	26.6	12.2	7.1	0.85

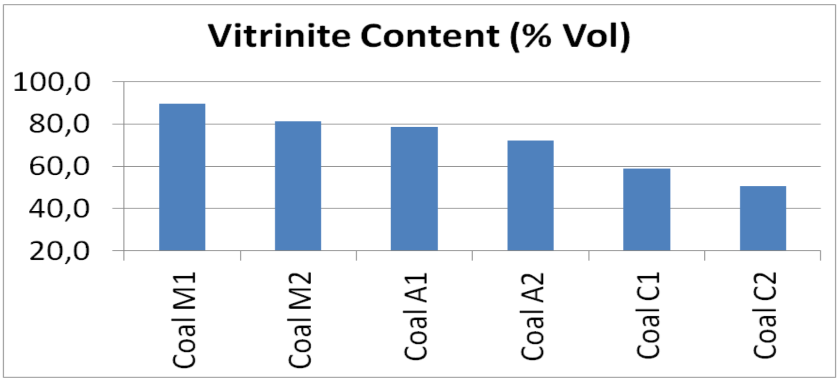

Figure 3. Vitrinite content for the different coals analyzed.

Comparing the Mozambican, Australian and Chinese coals selected for this study, it can be seen in Table 3 that a significant point of difference is the maceral composition, which is mainly related with the coal genesis.
Considering the medium rank coals, the Mozambique coals have higher vitrinite content than the Australian coals selected for this study (Figure 3). The level of vitrinite is much lower in these Chinese coals. With regards to the Mozambique coals, M1 has a rare content of vitrinite, its level achieves almost 90 vol.%. For M2 coal, the level is also very expressive, reaching over 80vol.%. Moatize mine is currently producing two hard coking coal products, both with vitrinite content around 81%.
Considering the exinite group, it can be noted that this maceral is absent in the Mozambique and Australian coals, which is normal in medium rank coals from these regions. On the other hand, in the low rank Chinese coals this maceral is generally present. Chinese coals tested showed a exinite level of around 10vol.%.

3.2 Mechanical Strength

The results of cold (M40 and M10) and hot strength (CRI/CSR) are shown in Table 4.

Table 4. Coke quality from 40kg pilot oven

Coal	Coke Quality (%)			
	M_{40}	M_{10}	CRI	CSR
M1	88.3	5.4	20.9	58.6
M2	84.8	8.8	18.0	62.6
A1	84.8	6.5	21.0	67.4
A2	81.6	7.5	31.5	50.7
C1	76.0	10.0	51.2	25.1
C2	80.0	9.0	38.1	46.2

Due to differences in operating conditions, it is not possible to directly compare these pilot scale results to industrial expectations. It is only fair to compare these coke quality results with those measured in the same pilot oven. For example, in industrial trials the CSR results for commercial versions of M1 and M2 coals are consistently greater than 64% and 69%, respectively. Furthermore, Coal A1 is a benchmark high quality hard coking coal with CSR reported at 74%. The lower CSR measurements from this 40kg coke oven tests compared to industrial expectations will relate largely to differences in bulk density and heating rates.
According a nomenclature adopted by CCRI, the cokes generated from Mozambique coals M1 and M2 are classified in a category of coals of First Grade of China Quality Standard for Metallurgical Coke. The First Grade classifications are due to high mechanical strength index (M40>80% and M10<7.5%), and high thermal strength index (CRI<30%, CSR>55%), which is specific to CCRI's pilot coke oven results. As expected, Coal A1 also is categorized as First Grade. Surprisingly, Coal A2, which is a well-known premium mid volatile coal with a CSR reported as 68% was categorized lower than both of the Mozambique coals.

3.3 Vitrinite X Mechanical Strength

The M40 and M10 indexes coals were plotted against vitrinite data (Table 2 and 3). So, the behavior of the mechanical cold strength for different levels of vitrinite is represented in Figures 4 and 5.

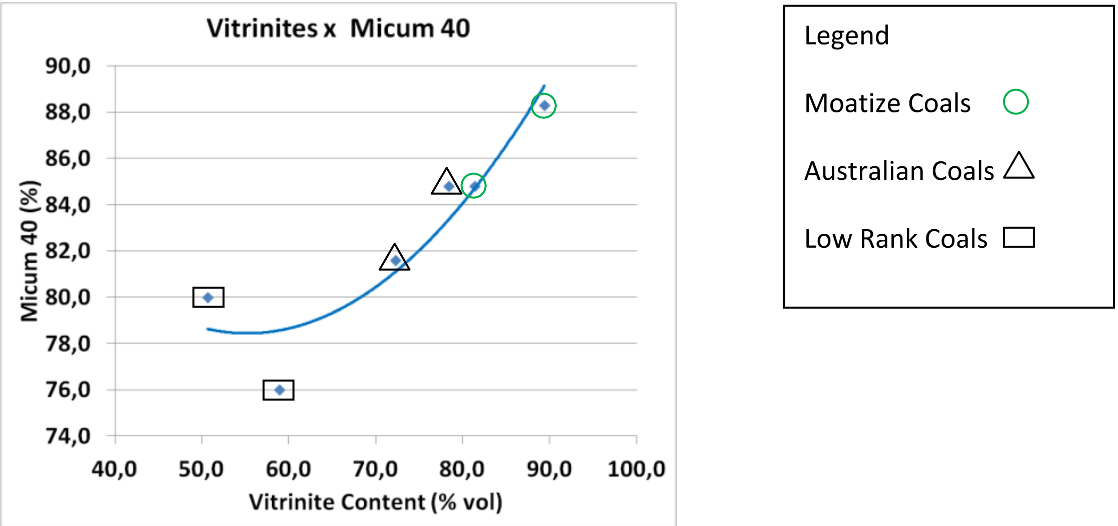

Figure 4. Vitrinite content versus M_{40},

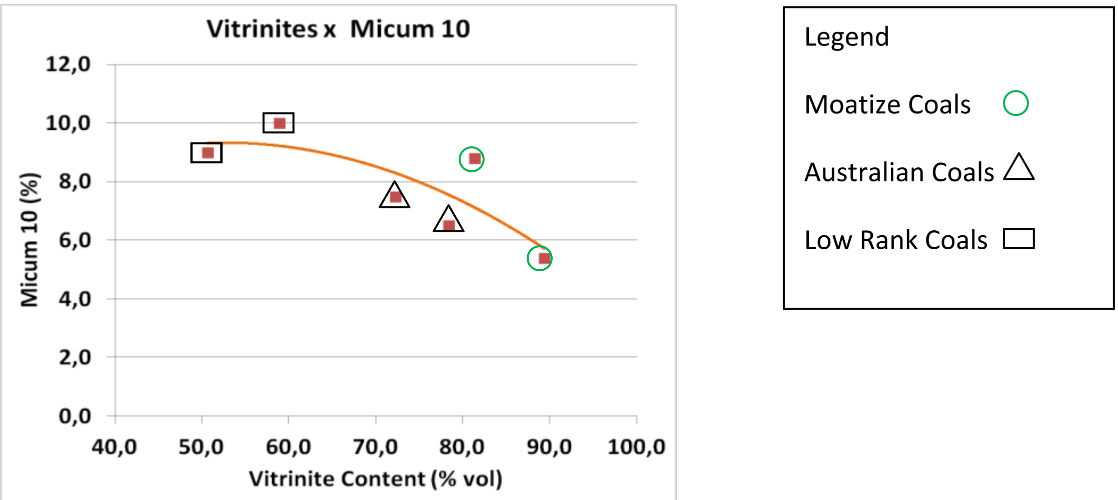

Figure 5. Vitrinite content versus M_{10}.

According Figure 4 it can be seen that vitrinite-rich coals have higher shatter resistance. The distribution of M10 results (Figure 4) shows that in these coals the abrasion resistance indexes are better (lower fraction < 10 mm after tumble drum testing).
Coals rich in vitrinite have better mechanical cold strength mainly because a higher content of vitrinite implies in a lower content of inerts into the maceral composition of the coals. In case of cold resistance, inerts act as nucleator and propagator of micro-cracks during solidification and semi-coke contraction, which make the coke structure less compact and less resistant.[1]
With regards to CRI and CSR, the relation between vitrinite content and these parameters are shown in Figures 6 and 7.

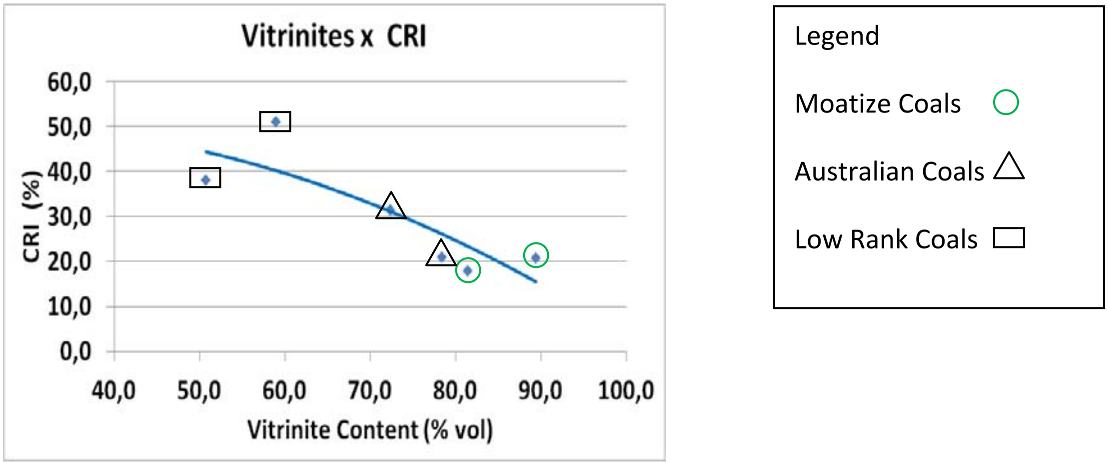

Figure 6. Vitrinite content versus CRI.

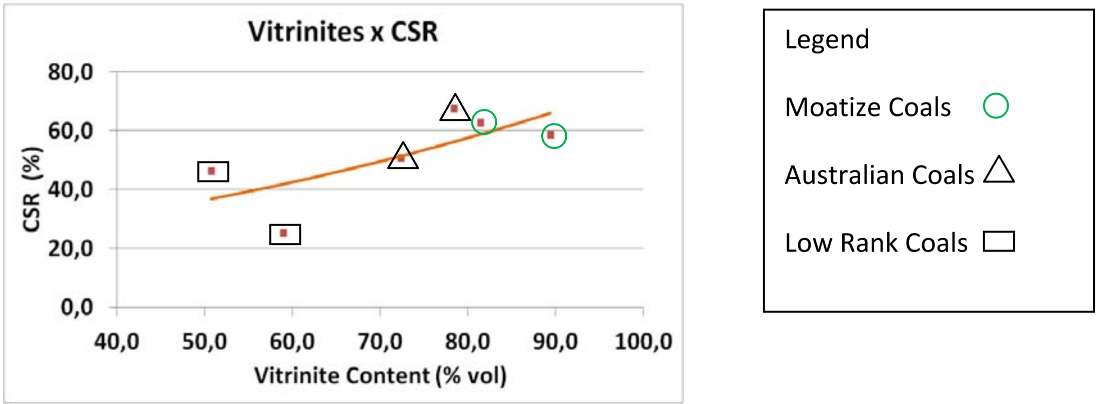

Figure 7. Vitrinite content versus CSR.

It can be seen that for vitrinite-rich coals the reactivity of the cokes are lower. The distribution of CSR results are showing that for rich vitrinite content the strength of coke after reaction with CO2 are higher. However, the impact of vitrinite on CSR appears to be less significant than the impact of rank on CSR (Figure 10).

The CSR/CRI behavior in relation to the vitrinite can be explained in terms of optical textures of the cokes. Inertinites have higher reactivity to CO2 due to higher levels of isotropic textures. Coals with high level of vitrinites consequently have low levels of inerts and hence have lower CRI.[(1)] Although not observed in this study, it is expected that as vitrinite content exceeds 90% the CSR will begin to reduce. This is observed in very high vitrinite coals such as those from Indonesia and is a result of insufficient inerts available to thicken the coke pore walls. Thin coke pore walls lead to increased degradation.[(1)]

It is also important to mention that in case of CRI the coal mineralogy, specifically the alkalinity index of ash, has an impact on the coke reactivity by catalyzing the Boudouard reaction.[(2)] The level of alkalinity index of these Australian and Mozambique coals is lower than 1.0, which is good for achieving lower reactivity of coke. Where coals from Moatize compare especially well to high vitrinite coals from other regions (and even within Mozambique) is in their superior ash chemistry. For example, high vitrinite coals from Indonesia and New Zealand generally suffer from high ratios of iron and alkalis in their ash. New Zealand high vitrinite coals also generally have above average sulphur levels.

3.4 R_{mm} X Mechanical Strength

The influence of reflectance (R_{mm}) on the coke cold strength as measured by the MICUM drum index (M_{40}) is represented in Figure 8.

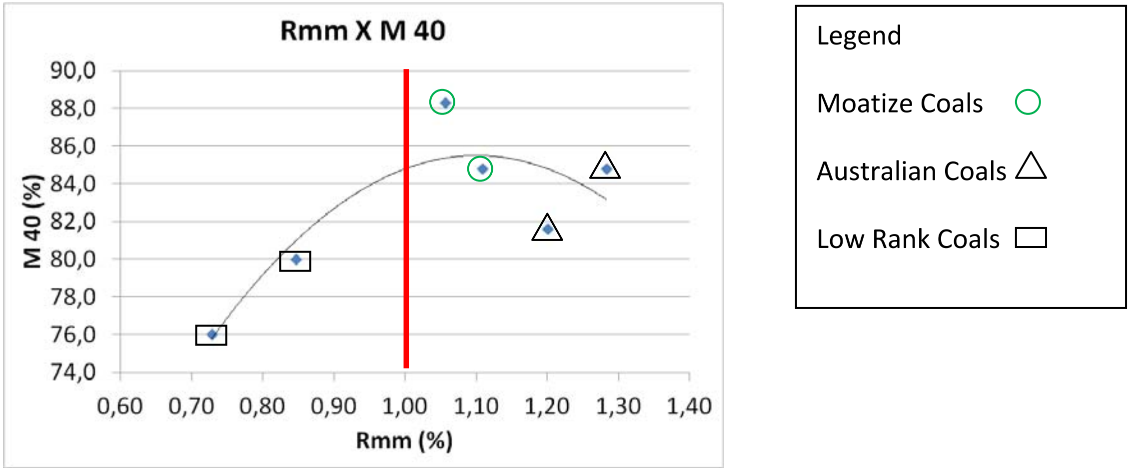

Figure 8. R_{mm} versus M_{40}.

In Figure 9 is possible to see that as the rank increases the M_{40} increases up until around 1.00% of R_{mm}. From that point to 1.30%, it seems that the R_{mm} does not have as much influence on the cold strength.[3]
This behavior is in general agreement to that observed by Reifenstein et al, 2005. According to that author, rank is limiting factor on coke cold strength up to around 1.10% of R_{mm} (Figure 9).

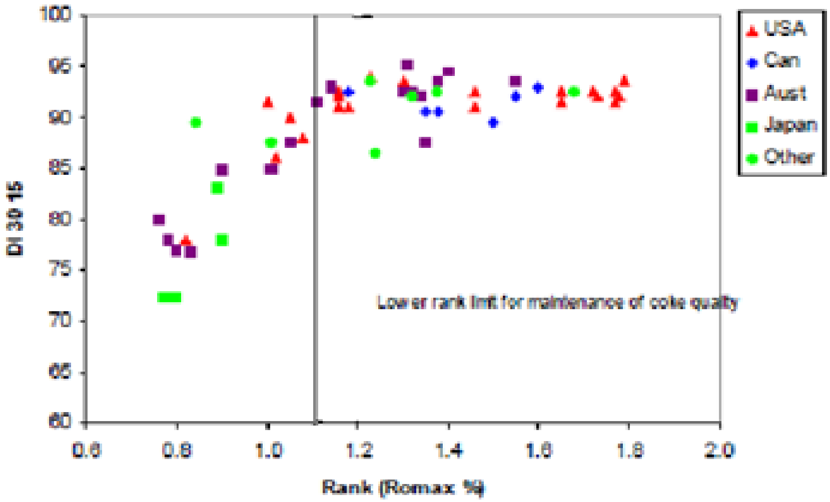

Figure 9. The rank limit for maintenance of coke quality.[3]

The relation between R_{mm} and coke hot strength (CSR) is represented in Figure 10. For this set coals, the higher the R_{mm}, the higher the CSR up until around 1.00%.[4] This is consistent with the behavior observed by Nakamura et al., 1977. According to that author, there is a close relationship between the CSR and the R_{mm} of the coal. The CSR passes through a maximum R_{mm} of 1.10% to 1.40%, which defines the region of prime coking coals, before dropping off again (Figure 11).

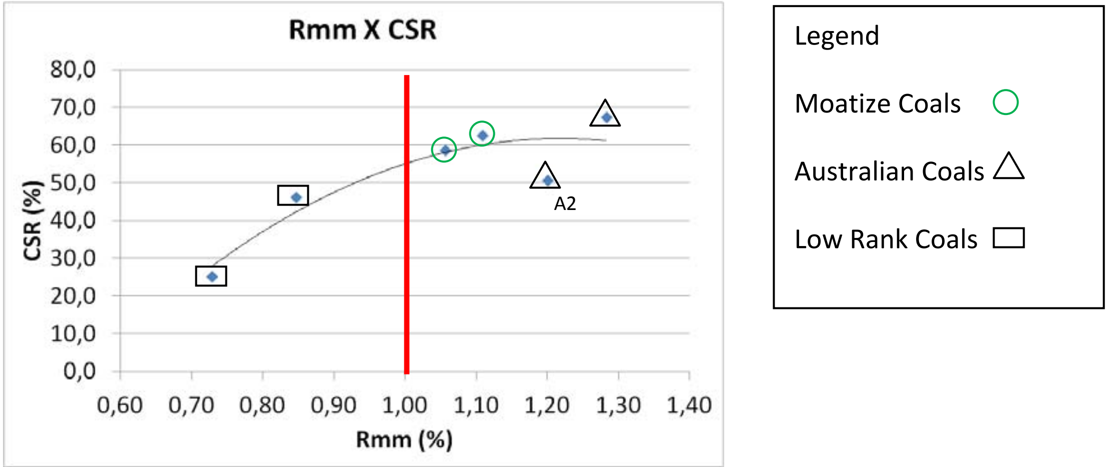

Figure 10. **Rmm** versus CSR.

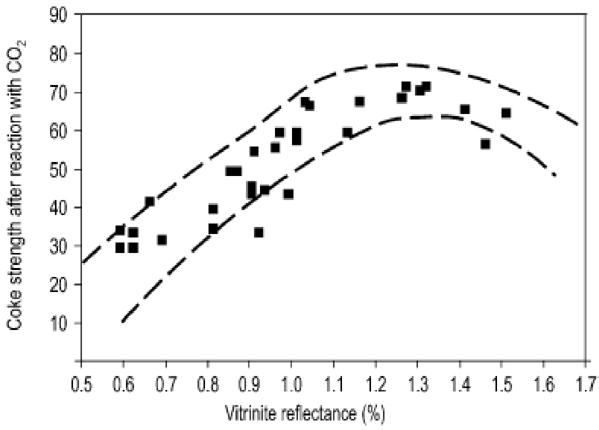

Figure 11. Relationship between vitrinite reflectance and coke strength after reaction with carbon dioxide (CSR index).[4]

Low rank coals (R_{mm} < 1.00%) generate cokes with more isotropic textures, which have lower mechanical resistance. These textures break in all directions due the random orientation of its crystallite.[5] Besides that, low rank coals, due to the high level of volatile matter, have higher contraction velocity during devolatilization. It promotes a lot of cracks and micro fissures in the coke. On the other hand, medium volatile coals and low volatile (R_{mm} >1.00%) coals generates cokes with higher level of anisotropy (textures kind of fibrous and flow) which have high resistance and more consistent structure with lower amount of fissures.[1] However, at ultra low volatile levels (R_{mm} >1.70%), the coal's chemistry changes sufficiently to reduce the rheological properties, limiting the ability of the coal to form cohesive coke, regardless of how much vitrinite is present.[4]

4 CONCLUSIONS

- According to the testing procedure and nomenclature adopted by CCRI, the cokes generated with Vale's Moatize coals are classified in a category of First Grade of China Quality Standard for Metallurgical Coke, due to their high mechanical and thermal strength index;
- in agreement to previous studies, Rmm was shown to have a strong impact on strength. Rank was observed to limit strength below a rank of about 1.1%, with less impact in the range of 1.1% to 1.4% reflectance. Whilst not observed

in this study, it is expected that going to Rmm >1.7% would begin to reduce the strength;

- vitrinite content was shown to have a strong correlation with both hot and cold strength indices. Within the set of coals studied, higher strength was achieved in the higher vitrinite coals. Whilst not observed in this study, it is expected that going to vitrinite >90% would begin to reduce the strength.

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