# CB17 - How the CPC Specification and Smelter Strategies Impact Performance and Anode Quality

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## Abstract

In this paper, an in-depth analysis of the effects of calcined petroleum coke (CPC) specification on the performance of aluminium smelters is conducted, mainly focusing on anode quality, energy efficiency, and environmental impact. First, historical trends of raw material petroleum coke are explored, examining the evolution of its properties over time and the factors affecting its quality. Then, to tackle the challenges and complexities of modern smelters, strategies employed by the industry, such as continuous supply management, supplier collaboration, and the implementation of process corrective measures, are investigated. Using the Emirates Global Aluminium (EGA) smelter as a case study, the impact of these strategies on anode quality and pot performance is discussed. Furthermore, a model that segregates the process and specification effects on anode quality is proposed, providing valuable insights for optimising smelter operations. Finally, a way forward is outlined, emphasising the importance of linking CPC specifications to potroom indices and financial key performance indicators (KPIs).

**Keywords:** Emirates Global Aluminium, Petroleum coke specifications, Calcined petroleum coke, Anode quality, Cell performance.

## 1. Introduction

Emirates Global Aluminium (EGA) owns and operates two smelters; the older Jebel Ali smelter, formerly known as Dubai Aluminium or DUBAL, is in the Jebel Ali Industrial Zone, Dubai. The newer Al Taweelah smelter, formerly known as Emirates Aluminium or EMAL, is in the Khalifa Port and Industrial Zone in Al Taweelah, Abu Dhabi, approximately 80 km east of Abu Dhabi.

### 1.1. EGA Background on the Aluminum Smelting Process

The production forecast of Jebel Ali smelter, Al Taweelah smelter and combined are listed in Table 1, highlighting the CPC consumption rates for both smelters.

**Table 1. EGA's approximate production forecast for 2023.**

| | **Hot metal production** (tpa) | **CPC consumption** ±5 % (tpa) | **Number of purchased anodes** |
|---|---|---|---|
| Jebel Ali smelter | 1 127 000 | 300 000 | 138 000 |
| Al Taweelah smelter | 1 519 000 | 585 000 | - |
| EGA | 2 665 000 | 885 000 | 138 000 |

While EGA produces almost 2.7 million tonnes per annum of hot metal, the actual production from EGA's own anode production is 2.3 million tonnes per annum; the remainder of EGA's hot metal production is from anodes purchased externally due to current limitations in the Jebel Ali plant. This capacity constraint is due to a significant amperage increase over the last 15 years in Jebel Ali smelter, exceeding its anode baking capacity. This paper will focus solely on in-house anode production and the metal made from these anodes.

## 2. Global Sourcing of EGA Coke Requirement.

EGA sources its 900 000 tpa (Figure.1) of coke from China, the USA, Germany, Brazil, Kuwait, Oman, and the United Arab Emirates. However, to obtain the required specification for EGA, nearly all these suppliers also source at least part of the GPC globally.

EGA's typical coke sourcing includes all three types of calciners: rotary, shaft, and minor amounts from rotary hearth calciners(Table 2)

**Table 2. Coke type vs calcination process.**

| → | Rotary Kiln | Shaft | Rotary Hearth |
|---|---|---|---|
| High-density (HD) coke | | F & G | D &E |
| Standard density (SD) coke | A, B & C | | |

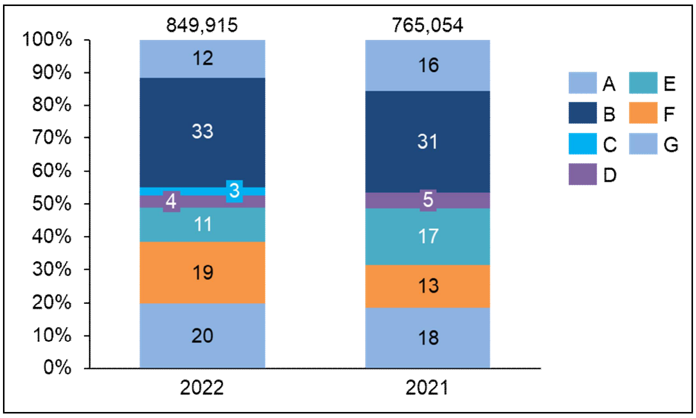


**Figure 1. Coke requirements 2022 vs 2021.**

## 3. CPC Coke Specifications and Historical Trends

The importance of CPC quality on smelter performance and anode quality must be balanced, with numerous CPC qualities having different and, at times, conflicting impacts on the final anode quality. The typical qualities, as shown in Table 3, are monitored and controlled in the EGA CPC specification, including:

Over the past decade, EGA has continuously improved its CPC specifications as part of a continuous improvement process to enhance overall anode quality. These improvements were made to meet the demands of reduction, mainly as the amperage increase necessitates EGA to operate some of the industry's highest anode current density potlines.

However, competing with the trend to tighten out CPC specification is the deterioration of various coke characteristics/properties by our suppliers due to changes in their GPC supply chain, including upgrades and other changes at their feeder refineries. Figure 2 demonstrates the variability of chemical and physical properties over the last ten years.

**Table 3. EGA's coke contractual specifications.**

| Particulars | Unit | Limits | | Preferred |
|---|---|---|---|---|
| Silicon (Si) | wt% | 0.025 | max | < 0.012 |
| Iron (Fe) | wt% | 0.025 | max | < 0.020 |
| Sulphur (S) | wt% | 2.8 | max | |
| Vanadium (V) | wt% | 0.024 | max | < 0.022 |
| Nickel (Ni) | wt% | 0.018 | max | < 0.016 |
| Calcium (Ca) | wt% | 0.012 | max | < 0.008 |
| Sodium (Na) | wt% | 0.01 | max | < 0.008 |
| Moisture (as received) | wt% | 0.3 | max | |
| Ash content | wt% | 0.2 | max | |
| Volatile matter * | wt% | 0.5 | max | |
| Real density | g/cm$^3$ | 2.05 - 2.07 | | 2.06 |
| Vibrated bulk density (SD CPC) | g/cm$^3$ | 0. 87 | min | |
| Vibrated bulk density (HD CPC) | g/cm$^3$ | 0. 91 | min | > 0.89 |
| Hardgrove grindability | HGI No. | 32 -40 | range | |
| CO$_2$ reactivity | % | 7 | max | |
| Granulometry (size) | | | | |
| + 30 mm | wt% | 0 | max | |
| + 4.76 mm ('+4 mesh) | wt% | 25 - 35 | range | |
| - 0.86 mm (-20 mesh) | wt% | 25 | max | |

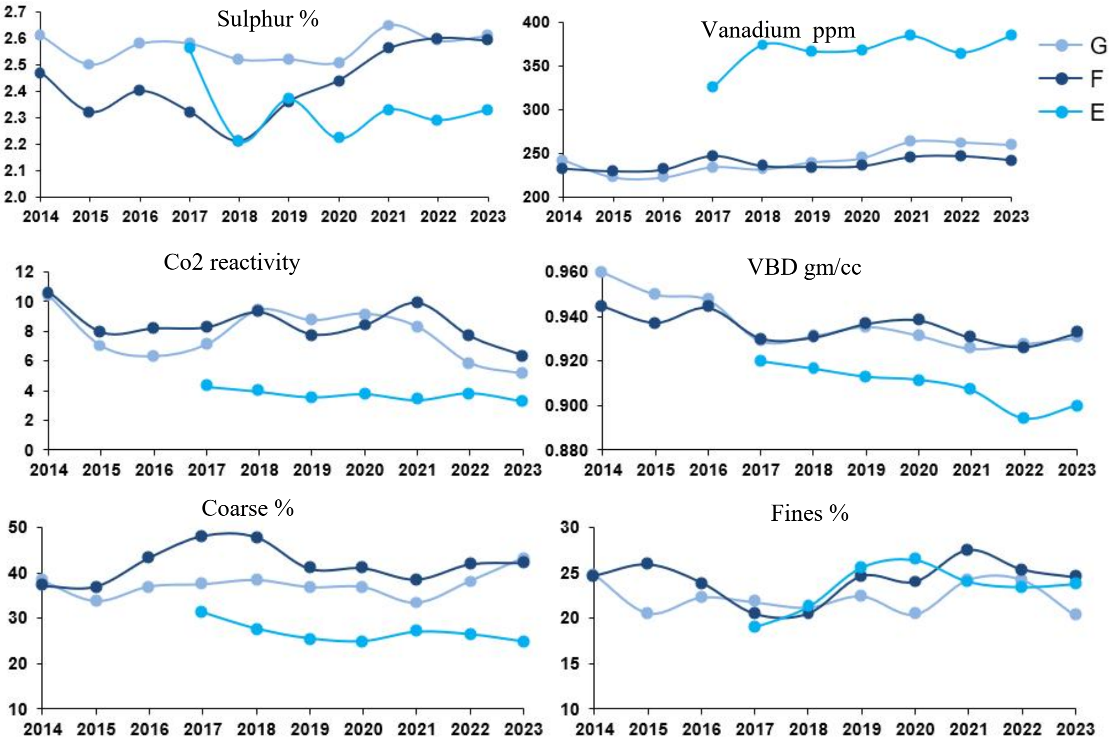


**Figure 2. Trends of some EGA's supplier E, F and G coke properties over the last 10 years.**

While most CPC specifications are designed to support the best possible anode quality and metal purity, sulphur is constrained to environmental concerns. EGA's current target is a maximum of 2.8 % due to local government regulation, which is expected to only get tighter over time.

Each coke exhibits different characteristics driven by the green coke source and calciners type. In Figure 3, coke type C is more advantageous than coke type A & B; however, sourcing the required type C coke is challenging.

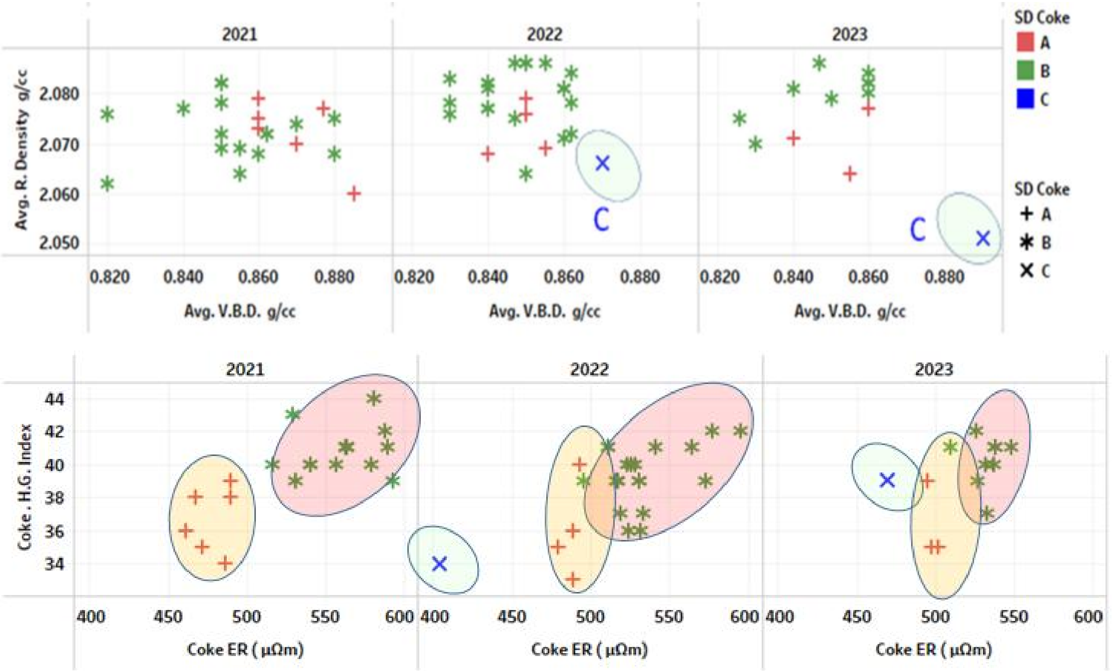


**Figure 3. Coke properties for coke type A, B and C. R.Density = real density, V.B.D = vibrated bulk density, ER = Electrical resistivity, H.G Index = hardgrove index.**

## 4. Sources and Manufacturing of Petroleum Coke and its Challenges

CPC is produced by calcining green petroleum coke (GPC), which historically is a waste product of carbon-rich residue from the oil refining process leftover after all the volatiles have been driven off, leaving long-chain petroleum hydrocarbons that are subsequently "cracked" into shorter chains via the coking process in the coker drum.

The purity and quality of the GPC are determined by multiple factors, including oil reserve, refinery design and process and local markets. However, the GPC is still the low-volume, low-value residue of the refinery process, whose quality control is not usually the key focus for the refinery (Figure 4a). Figure 4b shows a typical GPC product.

Issues affecting GPC supply are that GPC production rates are hard linked to oil refinery production. As such, a reduction in demand for oil products will affect the long-term supply availability of GPC. For example, in 2022, Phillips 66 and Marathon Petroleum announced they are moving ahead with projects to eliminate the processing of crude oil at refineries in the San Francisco Bay area by converting the sites to the production of renewable, drop-in transportation fuels using bio-based feedstocks which do not produce significant if any quantities of GPC. Additionally, as premium oil reserves are being consumed, the quality of the available GPC is slowly deteriorating; in particular, levels of vanadium and sulphur are slowly rising. While at the same time, the aluminium industry faces rapidly growing competition for premium cokes from the lithium battery industry, where the battery's cathodes require higher premium grades of CPC and are willing to pay a premium for it.

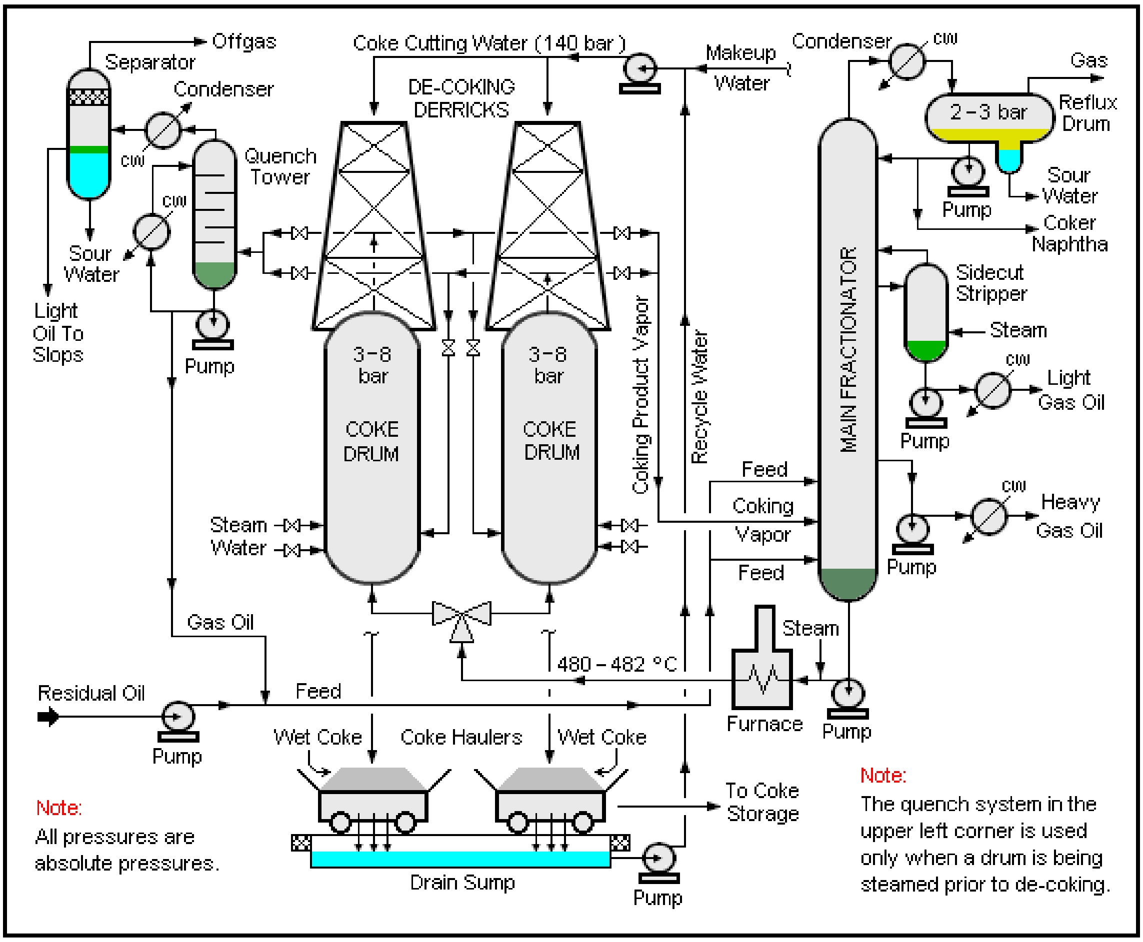


**Figure 4a. Typical coker process diagram.**

**Figure 4b. Typical GPC product.**

The GPC is physically drilled and subsequently removed from the coker drum. However, the GPC still contains approximately 5-20 % volatiles that must be driven off via a calciner to produce a granulated sponge-looking product (refer to Figure 5) suitable for anode manufacture.

**Figure 5. Typical appearance of coarse CPC.**

Anode grade GPC is typically low in sulphur (0.2-6 %) and metal impurities, affecting anode quality. It is also the primary source of $SO_2$ emissions from the smelter. Metal impurities in GPC affect both anode quality and final metal purity.

Conversion of GPC to CPC takes place in a calciner in three leading technologies.

- Rotary kiln,
- Shaft,
- Rotary hearth,

Regardless of the calcining technology employed, the process is still basically the same: to drive off the 5-20 % volatiles in the GPC in the calcining process, which takes place at a minimum of 1200 °C. Most of the volatiles are combustible and therefore used to provide all the required calcining energy, with some processes generating electricity from the excess energy from the calcining process.

One crucial factor distinguishing calciner technologies is their impact on vibrating bulk density (VBD). Rotary kiln technology typically results in lower density due to the faster heating process, leading to the formation of larger pores as volatile materials need to escape more quickly. This has a significant effect on the density of baked anodes. As a result, coke calcined from rotary kilns is known as standard-density (SD) coke and is seldom used in blends above 50 % in anode plants.

## 5. Strategy to Operate EGA Smelters

Different strategies were envisaged to minimise variability in the incoming CPC used for anodes manufactured at EGA. Some of them include:

- Collaboration with existing suppliers and tightening specifications
- Introduction of new suppliers
- Allocation of suppliers to a specific site
- Redefining the shipment parcel size.

### 5.1. Continuous Collaboration with Suppliers to Improve the Specifications

Over the past years, EGA has been working with a wide range of suppliers to keep up with its growing demand for anode production to maintain the uninterrupted operations of its reduction cells. We continuously collaborate with our suppliers, leveraging their unique offerings, including high-density (HD) CPC with a VBD over 0.92 g/cm$^3$ and standard density (SD) with a starting VBD of 0.80 g/cm$^3$. By visiting our suppliers' production sites, we gain insights into their capabilities and challenges, which helps build trust that the delivered product will meet our expectations. Recently, we have intensified our meetings with our suppliers, increasing the frequency from quarterly to monthly to ensure critical specifications, such as $CO_2$ reactivity, are met.

### 5.2. Changes in Specifications

Several approaches in the industry require tightening individual coke properties specifications. Others, like Azari et al. [1], explored the possibility of leveraging the combinations of raw material properties not compensated by the control schemes that can be identified. Multivariate specifications are required for these combinations to avoid a negative impact on process performance and end-product quality.[1]

Borràs-Ferrís [2] proposed a novel methodology for defining multivariate raw material specifications assuring quality with a certain confidence level for the manufactured product critical-to-quality attributes (CQA). The capability of the raw material batches to produce the final product with critical quality attribute (CQA) within specifications is estimated before producing a single unit of the product and, therefore, can be used as a decision-making tool to accept or reject any new supplier raw material batch [2]. We are exploring the novel methodologies implemented in the industry that could be a good fit for EGA. Currently, a simplified staged PLS model is used to assess the financial benefits or harmful effects of either drift in CPC quality change or process-related issues in the potrooms.

### 5.3. Introduction of New Suppliers

EGA has taken measures to reduce reliance on distant suppliers by engaging local providers. Securing local supplies of CPC coke reduces the cost and ensures a continuous supply to EGA. To ensure quality standards are met, EGA has implemented a strict process for evaluating every supplier of strategic raw materials. This includes lab testing conducted by EGA's lab and validation from a third-party lab. Additionally, a limited sample of anodes is produced and carefully tracked through the value chain to ensure that benefits and coke's impact are accurately assessed. While this process may require a significant effort, it ultimately ensures that EGA's supply chain is secure and that high-quality standards are maintained.

### 5.4. Allocation of Coke Suppliers by Site

With a site-specific approach, the coke supply was improved by considering each site's strengths and weaknesses. Factors like the sensitivity of the smelter to dusting and the storage flexibility were carefully considered. For instance, Jebel Ali smelter has five silos, making it possible to have more storage options than Al Taweelah smelter, which has only two large silos. This approach optimised the coke supply, improving efficiency and productivity.

### 5.5. Shipment Parcel Size

The parcel size has a notable effect on the particle sizing of the CPC. Specifically, with smaller parcel sizes ranging from 5 000 to 10 000 tonnes, there is a greater likelihood of coke mixing within the silo. This is particularly true for the larger (25 000 t) silos at Al Taweelah smelter.

The Al Taweelah smelter silos do not operate as "plug flow", and as such, there is considerable mixing at the interface between consignments as the silo is drawn down, driving off the particle size segregation. The segregation causes an uncontrolled progressive change in properties with the particle size range of one consignment mixing with a different particle size range of another consignment, thus making quality control in the green anode plant challenging at best.

Thus, large parcel sizes of, say 20 000 tonnes ensures the product quality from the discharge of the silo is relatively constant for extended periods, i.e., 20 000 tonnes at 750 tonnes a day is around 26 days of consistent supply.

## 6. Impact of Coke Strategies on Anode Performance

Not all CPC qualities are the same. The priority of CPC quality metrics was chosen based on their relationships or impact on the resultant anode quality and pot performance.

As Barry Welch says, 'Potlines is the customer', emphasising the necessary mindset of anode manufacturers [3, 4] to adhere to and even exceed customer expectations.

Some of the customer requirements, as described by Barry Sadler [5] in his postgraduate training course, are:

- Last cycle through adequate baked density, no premature failures)
- No metal contamination (high purity)
- Adequate strength/ high structural integrity (no cracks)
- Acceptable reactivity to air and CO$_2$, low dust propensity.

Managers must understand causal process maps well to comprehend how processes generate value for customers and the business. As shown in Figure 6, these maps provide a detailed breakdown of the sub-processes that make up a more extensive process. Causal maps [6] are crucial for a thorough top-down analysis to identify the root cause of issues such as baked density going out of control. They are also helpful for bottom-up process control and variation reduction by pinpointing the specific parameters that need to be focused on to meet customer requirements.

At EGA, a prime focus was given to minimising anode failures or incidents. Following the same principle as described in Figure 6 of data mapping, customer value measures (CVM) such as anode problems frequency or anode dusting were linked to the potential end-of-line (EOL) measures of anode quality like carboxy-reactivity dust (CRD) to their potential causal factors such as impurities and sulphur levels in anode and coke.

For example, Table 4 lists a few variables that may help reduce variability from an end-to-end value chain perspective.

**Table 4. Anode performance to coke key indicators. CRD = carboxy-reactivity dust, BAD = Baked apparent density, ER = Electrical resistivity, FS = flexural strength, CO2R = CO2 reactivity, VBD = vibrated bulk density, PSD = particle size distribution.**

| Potroom | Anode Dusting - Anode problems | | | | |
|---|---|---|---|---|---|
| Anode | CRD | BAD | ER | FS | Lc |
| Coke | Na, Ca, S, CO2R | VBD, PSD, | PSD, VBD | | Lc |

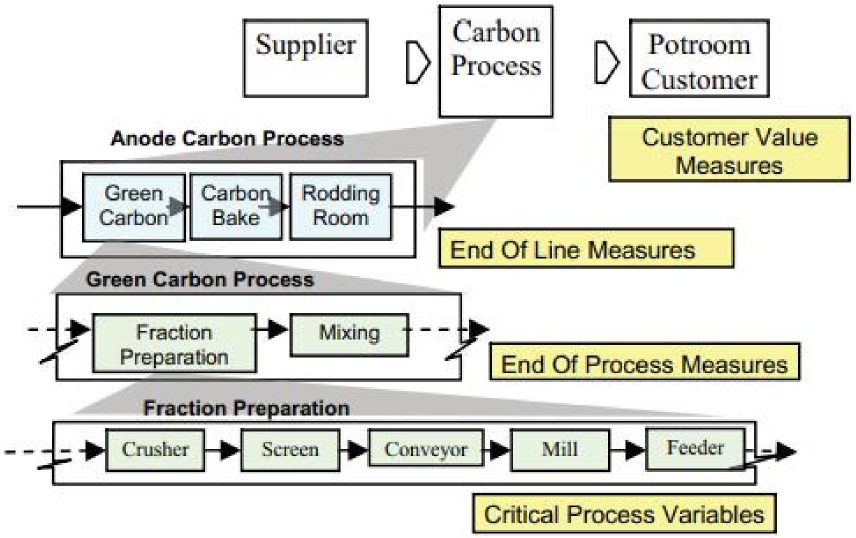


Figure 6. Process mapping vs data linkage [6].

## 6.1. Coke Suppliers versus Anode Quality

For two years, the anode quality data was analysed by coke blends. Each data point in the chart represents a coke blend with a blending ratio of 40 to 60 % of HD coke.

Figure 7 depicts three distinct clusters of anodes based on BAD and ER. These clusters naturally reflect the three sources of standard density Cokes A, B and C. C blended anodes exhibited superior anode quality compared to A & B anodes.

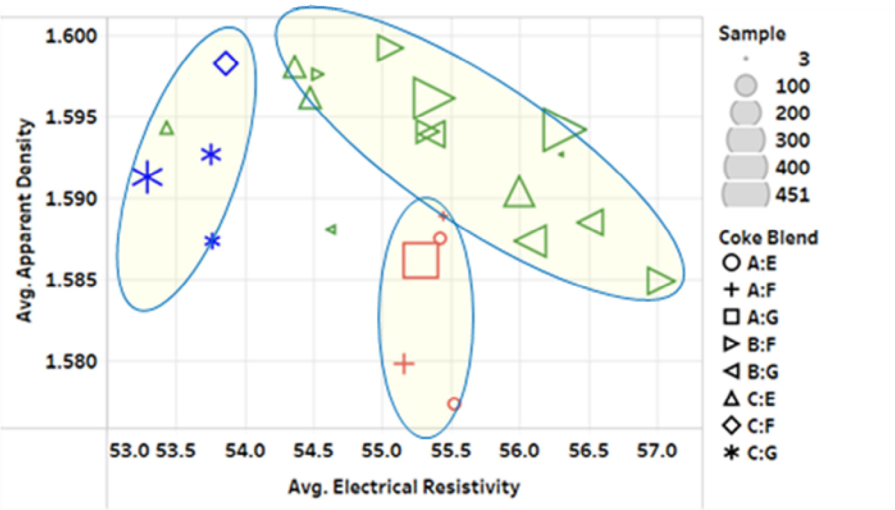


Figure 7. Anode quality of coke type C blended with E, F & G.

## 6.2. Coke $CO_2$ Reactivity versus Drivers

Coke $CO_2$ reactivity is driven by the green coke used and the manufacturing process blending either at the green stage or post calcination.[7,8,9]. The green coke will affect mainly its impurities levels such as Na, Ca and sulphur. A multivariate explanatory model was developed based on historical coke shipments supplied to EGA in recent years. The model outcome is well aligned with the common understanding in the literature [9]. Hereunder are some of the findings:

- Increased Na, Ca, and Fe impurities will increase the coke reactivity. However, increasing the sulphur content of the coke inhibits (locks) the reactive behaviour of Na and Ca catalysts, as illustrated in Figure 8.
- The coke's thermal history will affect its structure and porosity, for which coke Lc and VBD are good indicators/ proxies.[7, 8, 9]
- Blending is often used to improve the quality of existing single cokes. However, the interaction between Na+Ca vs S for some coke blends may not follow a linear relationship, as shown in Figure 9 with coke C.

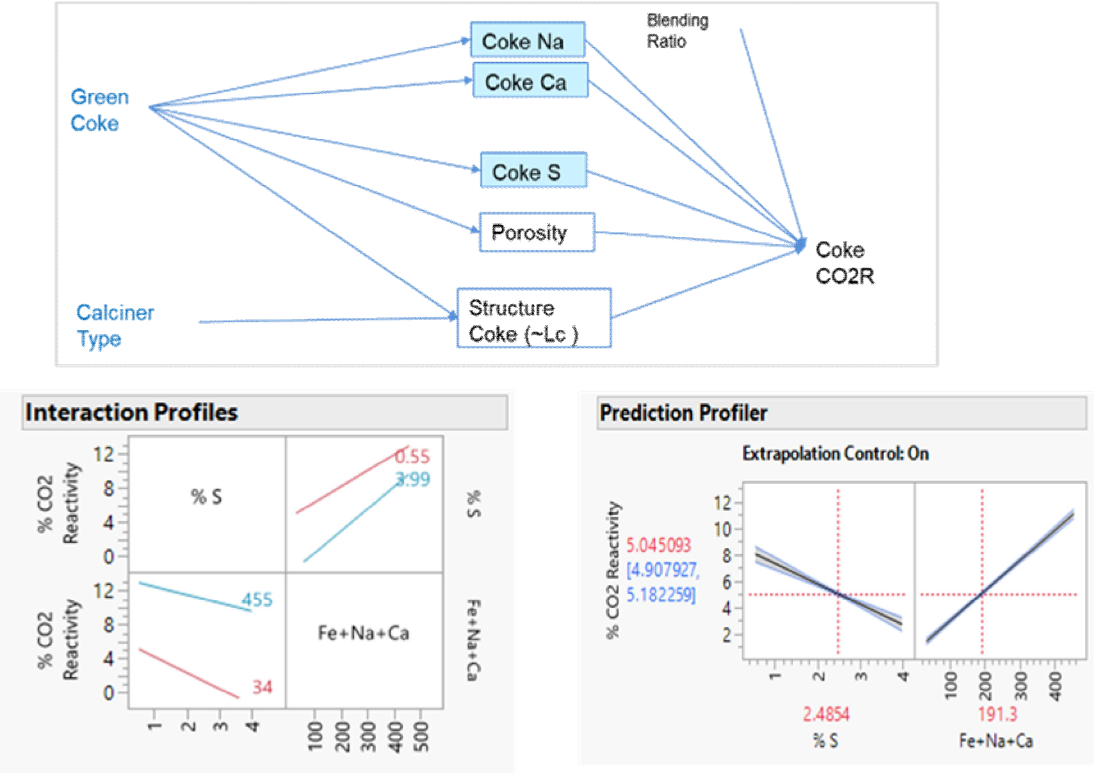


**Figure 8. Causal graph coke reactivity and interactive profilers.**

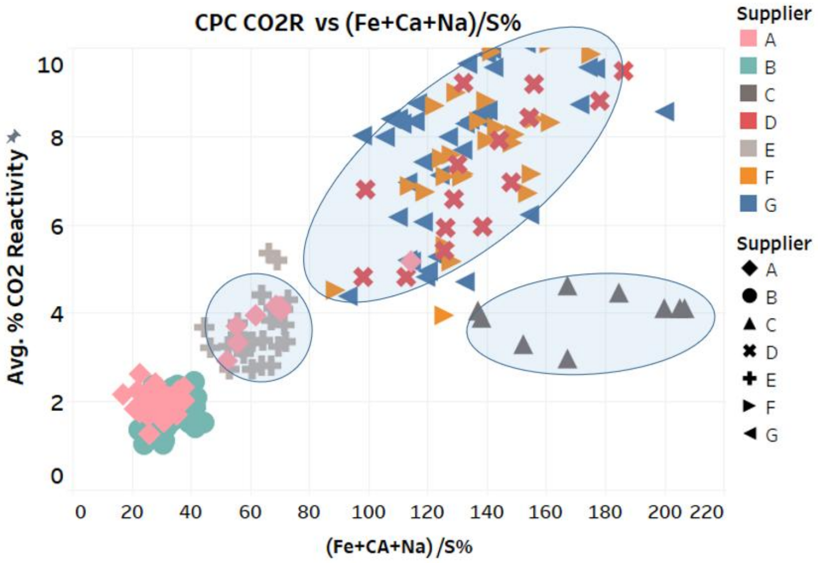


**Figure 9. $CO_2$ reactivity vs (Fe+Ca+Na) / S in coke.**

### 6.3. Example of Specification Change 1 – Coke $CO_2$ Reactivity

Over the last four years, as seen in Figure 10, the $CO_2$ reactivity of a high-density coke supplier has varied between 6 % and 12 %. EGA's governance and raw material team, equipped with the knowledge of CRD's importance to the smelter, brought attention to the variability and reviewed the specification from 12 % to 7 %. Following workshops and meetings, there was a noticeable shift in the shipments received, with most lab results falling below the 7 % compliance target.

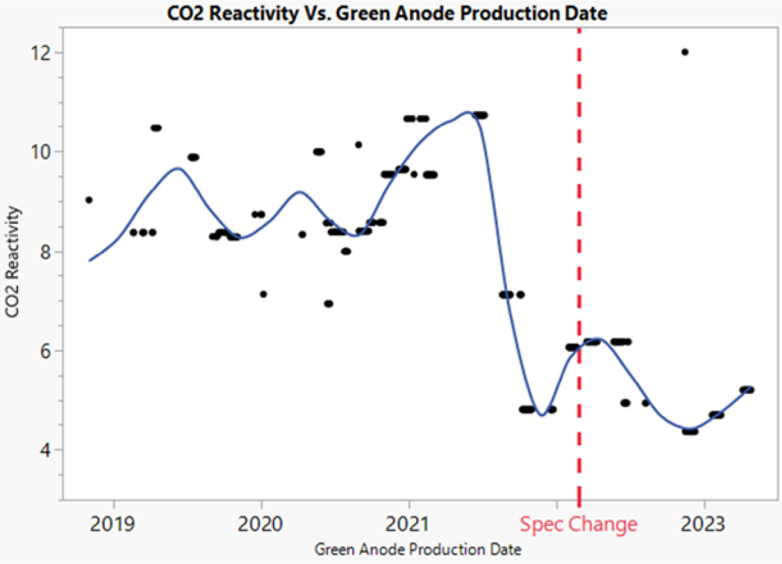


**Figure 10. $CO_2$ reactivity of a coke supplier over the years.**

### 6.4. Example of Specification Change 2 - Lc (Coke Calcination Level).

Due to the high demand for anodes, faster fire cycles are required. However, this can cause uneven heat distribution within the anode baking furnaces, potentially resulting in underbaking due to cold spots. To mitigate this risk, avoiding highly calcined coke above 28 Å is essential, as this can lead to dusting in the potrooms. To address this, a new specification range was shared with the coke suppliers, resulting in a positive outcome. As seen in Figure 11, recent shipments have shown a calcination level trending toward and below 27 Å.

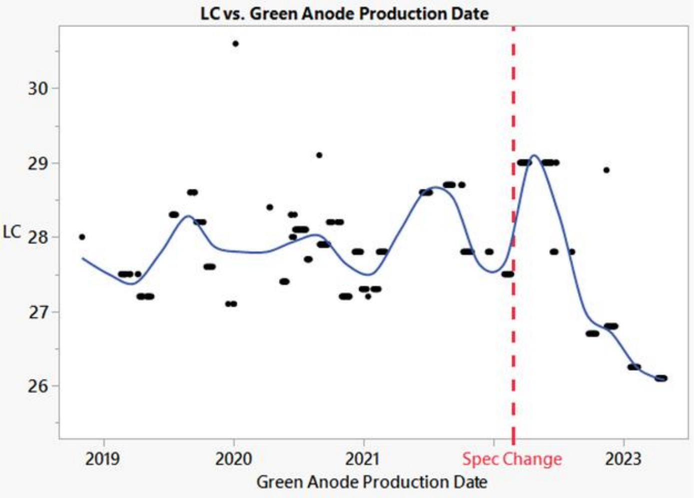


**Figure 11. Crystallite length of a coke supplier over the years.**

## 7. Is There Any Contribution to the Process?

Cautious to avoid 'shifting the blame' [3] to upstream (suppliers) as it is sometimes the case, the need for a model that segregates process vs specification effect on anode quality was obvious. A case study was conducted, focused on the value chain effect (coke to anode performance) of anode reactivity.

### 7.1. CPC to Anode Reactivity Model

The model links the anode constituents (coke, pitch and spent anode recycle) and its CRD. It determines the effect of the process (spent anode and baking levels), as not everything is influenced by the CPC. As depicted in Figure 12, a causal map was developed based on the process knowledge drawn from experience and available literature.

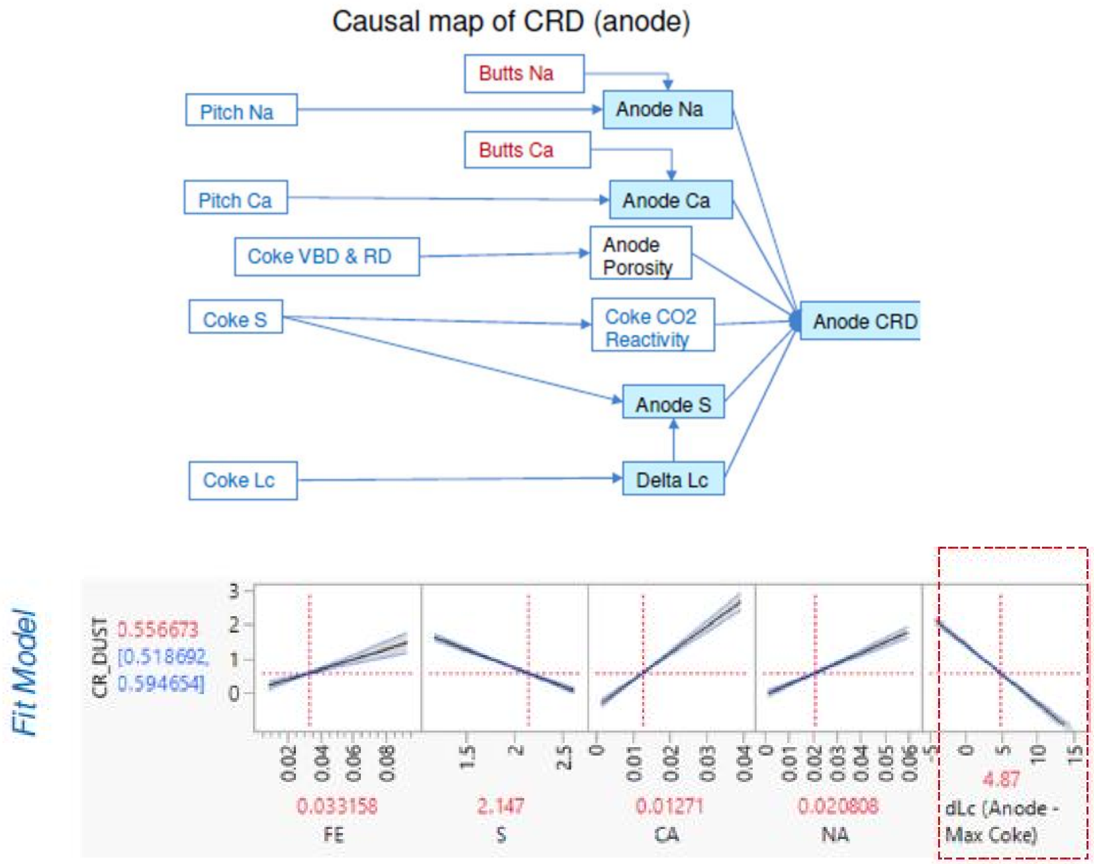


**Figure 12. CRD causal graph and few critical contributors.**

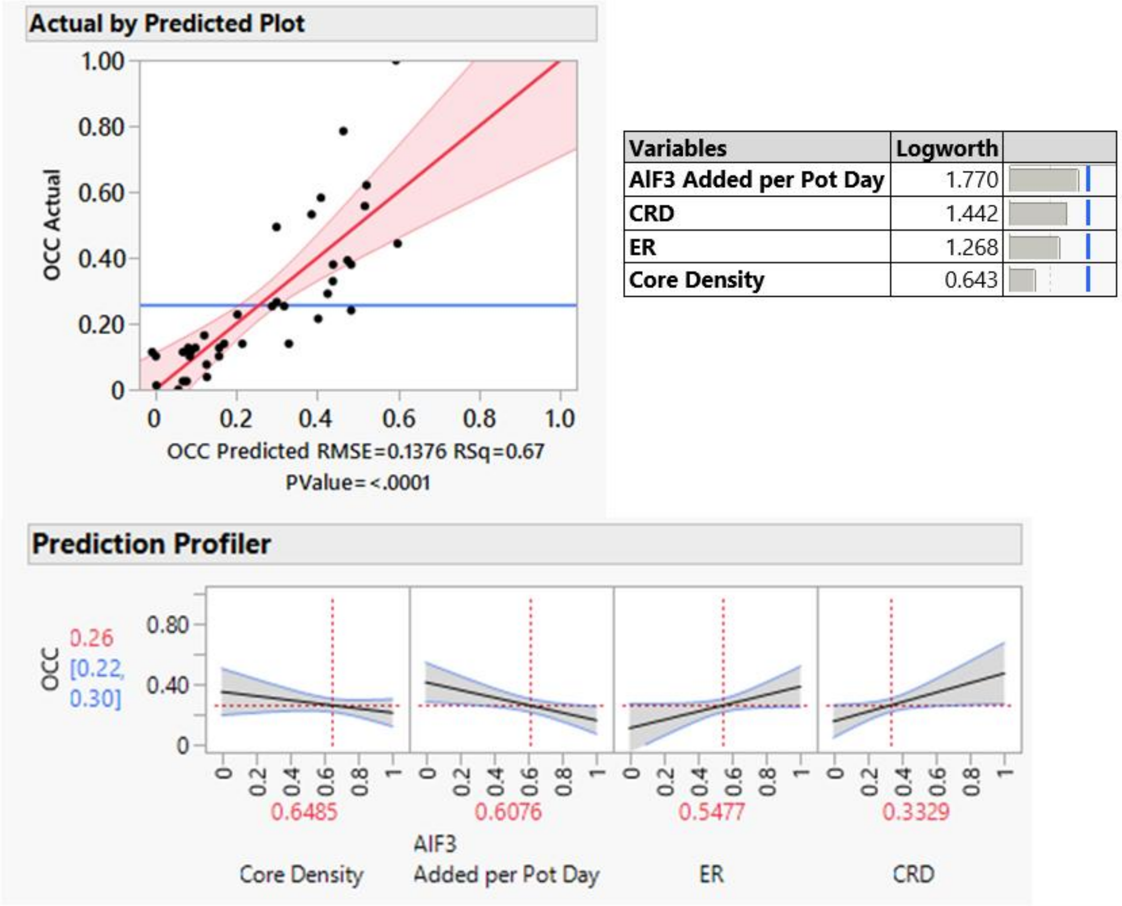
The model outcome is well aligned with the common understanding in the literature [9]. Multiple factors influence anode reactivity:

- $CO_2$ reactivity of the coke behaviour will be reflected in the anode CRD based on the adopted operating usage.
- Strategy.
- Na and Ca are known catalysts for carboxy reactivity and are inhibited by sulphur.
- Improved anode structure (crystallite formation), i.e. (differential Lc anode and coke), higher dLc improves CRD. Impurities coming from the spent anodes (butts) account for

a significant contribution to the impurities in the anodes and can be addressed to a greater extent by process control measures.
- Desulphurisation will deteriorate reactivity. However, depending on the nature of the coke's initial sulphur level [low – coke C and high coke A], its effect is not linear.

### 7.2. Anode Reactivity to Overall Carbon Consumption (OCC)

We have developed a model shown in Figure 13 to explain carbon consumption, considering mass balance net carbon, which includes dust from cleaning and disposed carbon material from the cells. Only 4 metrics, namely CRD, anode electrical resistivity (ER), Baked anode core density and $AlF_3$ daily additions to the pot, were considered inputs to the model. The data used covered the period of January 2020 to July 2023 and was pre-processed with a normalisation step of all the relevant variables in a range from 0 to 1. The model showed decent performance, with an r-square of 67 %. We found that, except $AlF_3$ additions, which reflects the potroom operator response to bath temperature swings, CRD and anode electrical resistivity (ER) were the largest contributing variable affecting carbon consumption, further aggravated by the challenging low anode-cathode distance operated in Al Taweelah smelter. Higher levels of CRD and ER led to higher carbon consumption. These findings align with general industry knowledge and have been vital in optimising our anode manufacturing process. For example, reducing the CRD by 0.5% will be equivalent to a 7 kg reduction in Carbon Consumption for this specific pot line.



| Variables | Logworth | |
|---|---|---|
| AlF3 Added per Pot Day | 1.770 | |
| CRD | 1.442 | |
| ER | 1.268 | |
| Core Density | 0.643 | |

**Figure 13. Normalised OCC model and a few critical contributors, data for year 2020 to July 2023.**

## 8. How These Actions Translate into Anode Quality and Pot Performance

Together with other initiatives EGA took [10, 11], there was a significant reduction in anode dusting levels, as shown in Figure 14. At Al Taweelah smelter phase 1, high levels of CRD were almost associated with high dusting cells being reported.

Anode dusting is one of the key symptoms of something dysfunctional in the pot, evidenced by the percentage of carbon in the anode cover material. Other factors include reacted alumina from anode baking furnaces which is added to the gas treatment centre with a higher share of pots on iron attacks. These additions may also contribute to the carbon content in the anode cover rising to higher levels (Figure 15). In this specific context, the carbon content (tar) coming from reacted alumina, also called kiln alumina, did not show much effect as compared to carbon dust resulting from the anodes and indicated by high CRD values, as demonstrated in Figure 15. The dusting propensity is strongly dependent on the differential between coke calcination temperature and anode baking furnace baking temperature (either under-baking or over-baking with desulphurisation), sodium and calcium levels in the binder matrix and finally, on reduction cell operations as shown earlier, in the paper (Figure 12).

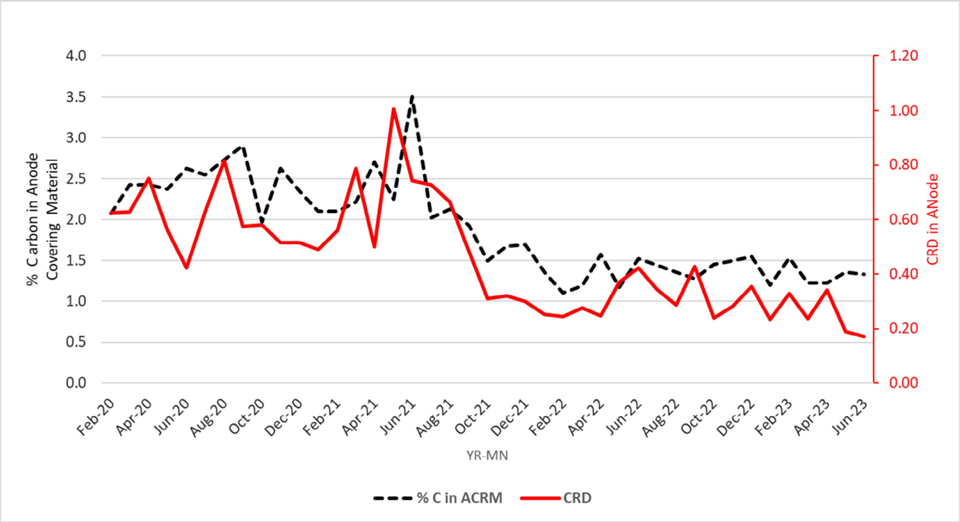
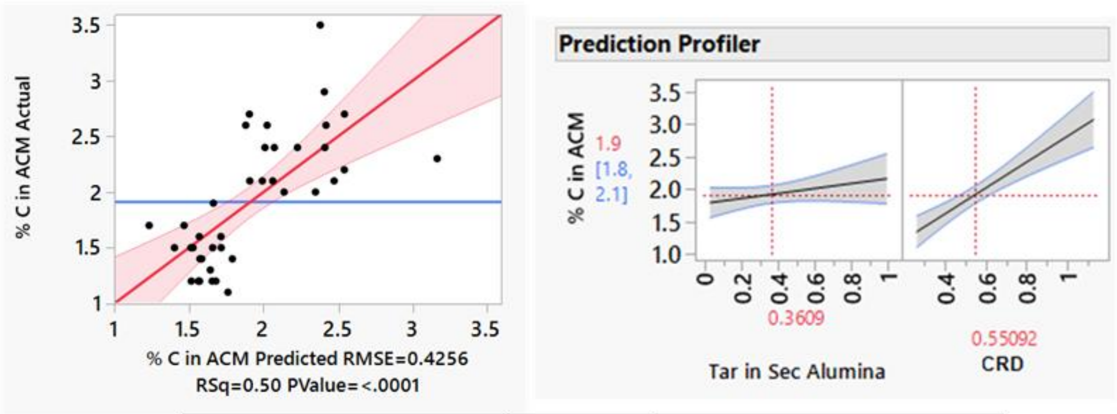


**Figure 14: Carbon % in anode covering material vs CRD (Year-MN = Year-Month).**



| Variables | Log worth |
|---|---|
| CRD | 5.813 |
| Tar in Secondary Alumina | 0.739 |

**Figure 15: Explanatory model for % carbon in anode cover vs drivers.**

## 9. Linking Coke Specifications to Potroom Indices and Financial KPIs

Leveraging the OCC model, different coke blends could be assessed, changes in their specifications simulated and sensitivity analyses developed. For example, Figure 16 depicts how standard coke density (SD) C outperforms other SD cokes (A &B) irrespective of the high density (G, F, E) with which it is blended.

A gap of approximately 4 kg C/t Al between the best coke combination C+E vs B+F (highest value) is observed. Given the assumption that 1 kg C/t Al is equivalent to 2 million USD at the scale of EGA, there is an 8 million USD per annum incentive if the CPC differences are minimised.

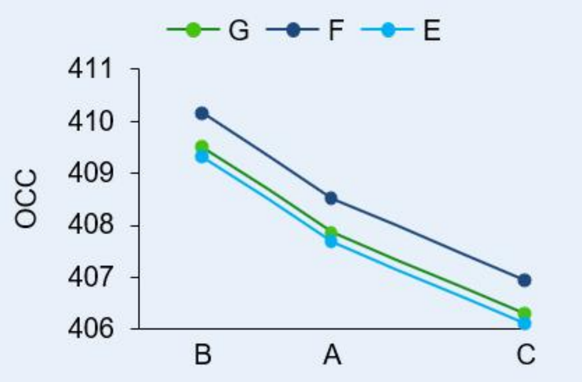


**Figure 16. Carbon consumption vs coke blend type.**

## 10. Investing in Research and Development for Alternative Raw Materials

Given the size of EGA's smelters, acquiring the infrastructure for in-depth research and development is recommended for carbon anode manufacturing.

Anode pilot plant facilities are being explored and are listed in the capital expenditure program.

## 11. Conclusions

This paper provides an in-depth analysis of the effects of calcined petroleum coke (CPC) specifications on the performance of aluminium smelters, focusing on anode quality. It covers historical trends of raw material petroleum coke, strategies employed by the industry to tackle challenges, and the impact of these strategies on anode quality and pot performance using the Emirates Global Aluminium (EGA) smelter as a case study.

This study detailed steps to enhance smelter performance, reduce costs, and improve environmental sustainability through better coke specification and process optimisation. By adopting these recommendations, aluminium smelters can achieve higher anode quality, increased energy efficiency, and reduced environmental impact, contributing to the overall growth and sustainability of the industry.

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