

REVIEW ON CALCIUM CARBIDE PRODUCTION USING LOW-RANK COAL AS REDUCTANT

Onesimus BALOYI, Michel Kalenga WA KALENGA

University of Johannesburg, Faculty of Engineering and Built Environment, School of Mines, Metallurgical and Chemical Engineering, Johannesburg, South Africa, michelk@uj.ac.za; balyionesimus@gmail.com

<https://doi.org/10.37904/metal.2026.5268>

Abstract

Calcium carbide (CaC_2) is a vital industrial chemical, central to acetylene production, metallurgy, and chemical synthesis. South Africa, leveraging its coal reserves and metallurgical expertise, has recently entered the global market as a calcium carbide producer. However, the sector faces a major challenge: South Africa's energy crisis. Calcium carbide production, conducted in electric arc furnaces (EAFs) at 2000–2200 °C, is highly energy-intensive, consuming over 3–4 kWh per kilogram. With rising tariffs and unstable supply forcing many energy-intensive industries to shut down, therefore innovation is required. Recently, substituting anthracite with low-rank coals which offer greater reactivity, usage of lime-coal pellets are amongst several strategies to reduce energy consumption without compromising product quality. The addition of fluxes such as CaO to lower the effective reaction temperature is a plus. This study investigates the combined effects of low rank coal as a reductant, flux addition and pelletized feed for calcium carbide production. Using controlled carbothermal reduction experiments, supported by X-ray fluorescence (XRF), X-ray diffraction (XRD), and Scanning electron Microscopy (SEM), the work evaluates reduction kinetics, slag behaviour, and carbide yield. Response Surface Methodology (RSM) is applied to optimize variables and quantify their impact on energy efficiency. Preliminary insights emphasize slag chemistry as a critical factor in lowering thermal demand while preserving product purity. Results obtained demonstrate that the formation of CaC_2 was effective at relatively low temperature and that the reactivity of the low-rank coal used is good enough to replace generic high-quality coal. By addressing the energy constraints, this research supports industrial resilience while contributing to Sustainable Development Goals (SDG 9 and SDG 12). It advances the case for greener, more sustainable pathways in one of the world's most energy-intensive industries.

Keywords: Metallurgy, Calcium Carbide, production, review, Low-Rank coal

1. INTRODUCTION

The current means of CaC_2 production require temperatures well above 2000 °C, heated in an electric arc furnace. With an exorbitant energy consumption of about 3250 kWh/t for a CaC_2 product of 80% purity [1,2]. This is a major concern surrounding this industry, more in particular in South Africa's case where energy is huge crisis. This sees the CaC_2 facing closure. Several studies have been conducted to reduce energy consumption, different feed type [3] auto-thermal CaC_2 production [4], low rank coal [5] and flux additives. Raw material is crucial as it directly influences the final product in terms of yield and quality of CaC_2 produced. The influence of lime composition has a significant influence as it impacts the CaC_2 product that meets market standards (80% purity). At most, Industrial-grade anhydrous lime should contain at least 95% calcium oxide, with impurities limited to 5% [6]. Studies have shown that lime containing more than 3% MgO negatively impacts the reaction, as magnesia does not interact with either lime or carbon, effectively acting as a physical barrier that prevents CaC_2 or rather reduces the reaction kinetics. The choice of carbon source plays a critical role in reaction kinetics, temperature requirements, and final carbide purity [7]. Research indicates that coke and charcoal exhibit superior performance over anthracite, primarily due to their higher porosity and reactivity [5]. The porosity of the carbon source influences gas permeability in the furnace, facilitating more efficient

carbon volatilization and carbide formation [8]. Charcoal has been found to yield exceptionally pure carbide due to its low ash content [9]. However, its high cost and low density present operational challenges, as fine charcoal particles are easily carried away by furnace gases, leading to material losses. Anthracite, while readily available and cost-effective, is less reactive due to its dense structure, which can hinder carbon diffusion and carbide formation at lower temperatures. The depletion of high-ranked coal makes the production of calcium carbide not only expensive but lowers the quality of the products. The current study reviews calcium carbide production using Lo-Rank coal to assess the effectiveness of phases formation at relatively low temperature to ascertain the reactivity of the coals used.

2. MATERIALS, EQUIPMENT AND EXPERIMENTAL METHOD

2.1 Materials and equipment

Two Low-Rank coals were used in this study. The coals originated from South Africa in the Southwest region. Two different lime samples were used to test their effectiveness. XRF and XRD were used for elemental characterization of the samples including ashes from coals and mineralogy while proximate analysis was performed on the coals to determine fixed-C.

2.2 Experimental method

A mixture of raw material (lime and coal) was made for the main objective of this study, so to evaluate the effect of using low-rank coal as a substitute for raw anthracite. Based on the reactivity analysis, the best lime (highly reactive) and coal (highly reactive) were combined. The mixture of raw material between lime and coal to establish a molar ratio. The combinations were established in that a mixture of 70 % of the best lime and 30% of low lime and 100% of the coal, and vice versa for the second mixture as illustrated in Table 1. The control mixture (100% best lime and 100% best coal) was therefore used to evaluate the relationship between pressure, temperature and composition relation at temperatures of 1500°C and 1700°C.

Table 1 Experimental matrix

Mixture	Raw Material		
	Lime	+	Coal
M1	100% best	+	100% best
M2	100% best	+	70% best + 30% low
M3	70% best + 30% low	+	100% best

Experiments were carried out in an alumina tube furnace (THM 15) at a heating rate of 7°C/min. Argon gas was blown in the furnace to minimize the interference of the graphite crucible. A graphite crucible was used to best emulate industrial scale CaC₂ production process.

3. RESULTS AND DISCUSSION

3.1 Coal reactivity

Table 2 present results of the petrographic analysis of the two coal samples provides important insight into their expected combustion behavior and overall reactivity while **Table 3** shows the XRF results of the two coals and **Table 4** Vitrinite reflectance analysis by Ro volume percentage. It transpired that Coal 1 contains a vitrinite content of 50.9% (54.2% mmf), while Coal 2 has a lower vitrinite content of 42.4% (43.8% mmf). Vitrinite is the most reactive maceral group in coal, characterized by its ability to devolatilize more readily and ignite faster during combustion. Therefore, the higher vitrinite concentration in Coal 1 indicates that it possesses greater inherent reactivity. In contrast, inertinite levels are substantially higher in Coal 2 at 54.4% (56.2% mmf),

compared to 42.9% (45.8% mmf) for Coal 1. Inertinite is known for its low reactivity due to its denser structure, higher degree of carbon ordering, and resistance to thermal decomposition, leading to slower burn rates and reduced char reactivity. Both samples show no liptinite content, meaning no additional contribution to reactivity from this high-volatile maceral group. Mineral matter content is slightly higher in Coal 1 (6.2%) than in Coal 2 (3.2%), relatively minor difference and does not outweigh the dominant influence of maceral composition on reactivity. Overall, the balance between vitrinite and inertinite is the key determinant, and the significantly higher vitrinite proportion in Coal 1 makes it the more reactive coal. This implies that Coal 1 ignites more easily, release volatiles more efficiently, and produces a more reactive char versus the more inert-rich and therefore less reactive Coal 2.

Table 2 Maceral group analysis by volume percentage.

Sample identity	Coal 1		Coal 2	
Maceral group	<i>linc. mm</i>	<i>mmf</i>	<i>linc. mm</i>	<i>mmf</i>
	Volume %		Volume %	
Vitrinite	50.9	54.2	42.4	43.8
Inertinite	42.9	45.8	54.4	56.2
liptinite	0.0	0.0	0.0	0.0
Mineral matter	6.2		3.2	

Table 3 XRF results of the two coals used (mass %).

Component	Na ₂ O	Na ₂ O	Na ₂ O	Na ₂ O	Na ₂ O	Na ₂ O	Na ₂ O	Na ₂ O	FeO
Coal 1	0.18	0.27	23.18	40.71	0.07	0.37	2.45	2.76	30.01
Coal 2	0.11	0.40	21.00	41.89	0.33	2.52	3.08	6.45	24.22

The petrographic images provided, alongside the maceral composition data and vitrinite reflectance analyses, collectively illustrate important differences between Coal 1 and Coal 2. The images clearly show the dominant maceral groups primarily vitrinite and inertinite and visually support the numerical maceral proportions previously discussed. In **Figure 1**, the micrographs show a greater distribution of vitrinite material, typically represented as homogenized, grey-toned, and moderately reflective organic bands. These vitrinite bands, relatively uniform in texture, consistent with the higher vitrinite percentage reported in the maceral analysis (54.2% mmf). Vitrinite's structure allows for greater devolatilization and easier ignition, corresponding with the earlier conclusion that Coal 1 is more reactive. The reflectance values ($R_{max} = 3.12\%$) further classify the vitrinite as high rank, but still marginally less mature than that of Coal 2, which reinforces Coal 1's comparatively greater reactivity.

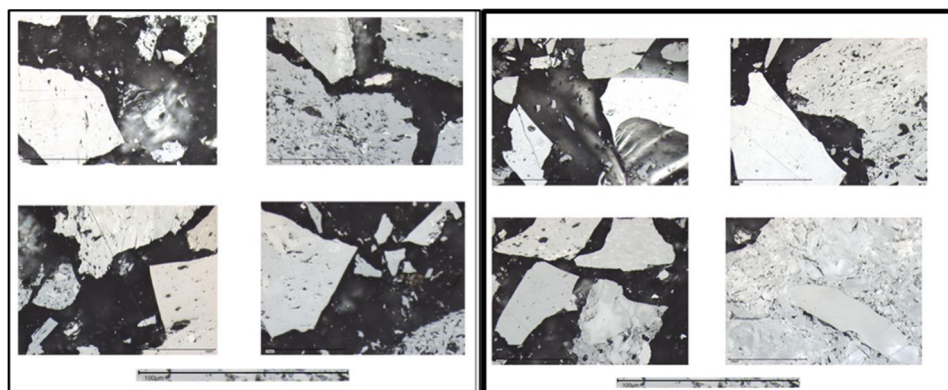


Figure 1 Coal 1, Coal 2 Micrographs

However, Coal 2 exhibits a visibly higher concentration of inertinite macerals, recognizable through their brighter, more reflective appearance and often more angular or granular textures. This aligns with the higher inertinite proportion observed in Coal 2 (56.2% mmf). Inertinite macerals originate from precursors subjected to oxidation, charring, or natural burning processes before burial. They are more carbon-rich, aromatic, and resistant to thermal breakdown, which directly reduces coal reactivity during combustion. This visual evidence is strengthened by the vitrinite reflectance analysis, where Coal 2 shows a slightly higher R_{max} value of 3.22% and a notably wider reflectance range (2.25–4.75%), suggesting a more heterogeneous and overall, more mature carbon structure. The high maximum reflectance values visible in some inertinite particles correspond with the bright, highly reflective inertoid structures depicted. Such petrographic features indicate low reactivity and slow char burnout in combustion or gasification processes. Further, the petrographic variability captured in the standard deviation values 0.364% for Coal 1 and 0.461% for Coal 2 correlates with the visual observations. Coal 2 micrographs display more structural heterogeneity, a reflection of its higher inertinite content and broader scatter of reflectance readings which indicate inconsistent combustion behavior. Conversely, the more uniform vitrinite distribution in Coal 1 points to a more consistent and reactive fuel, with improved devolatilization and flame stability. The vitrinite reflectance analysis (RoV%) for Coal 1 and Coal 2 provides key information on the rank, thermal maturity, and expected combustion behavior of the two samples. Vitrinite reflectance is a widely accepted indicator of coal rank, with higher reflectance values representing more mature, carbon-rich, and less volatile coal. Coal 1 exhibits an R_{max} value of 3.12%, while Coal 2 shows a slightly higher R_{max} of 3.22%, meaning that both coals fall within the high-rank category consistent with anthracitic or meta-anthracitic characteristics. The slightly higher reflectance of Coal 2 implies an even greater degree of coalification, meaning its carbon structure is more ordered and less reactive. The standard deviation for Coal 1 (0.364%) and Coal 2 (0.461%) reflects the variability within the measured particles. Coal 2's higher variability suggests greater heterogeneity in maceral reflectance, which aligns with its higher inertinite content observed in the petrographic analysis, as inertinite tends to have higher reflectance and contributes to a broader reflectance range. The maximum readings of 4.050% (Coal 1) and 4.750% (Coal 2), along with respective minimum readings of 2.150% and 2.250%, further Coal 2 contains a wider spread of reflectance values, again indicating structural heterogeneity and a higher proportion of highly mature carbonaceous material. The number of measured points (209 per sample) ensures statistical reliability of the dataset. Collectively, these reflectance characteristics reinforce that Coal 2 is the less reactive of the two samples due to its slightly higher maturity and more inert nature, while Coal 1, though still high-rank and relatively low in inherent reactivity, remains the more reactive coal when comparing the two.

Table 4 Vitrinite reflectance analysis by Ro volume percentage

Sample identity		Coal 1		Coal 2	
Vitrinite reflectance	R_{max}	3.12	%	3.22	%
(RoV%)	Standard deviation	0.364	%	0.461	%
	maximum reading	4.050	%	4.750	%
	minimum reading	2.150	%	2.250	%
	number of points	209		209	

3.2 Lime reactivity

The lime reactivity graph in **Figure 2** compares the reaction behaviour of two limestone samples, Lime 1 and Lime 2, based on their titration response to hydrochloric acid over a 16-minute period. Both samples show an initial slow reaction phase between 4 and 5 minutes, where reactivity remains below 100 mL, indicating that the acid–lime interaction is only beginning. This is followed by a sharp rise between 5 and 7 minutes for both samples, where reactivity increases rapidly from approximately 100 mL to between 250 and 300 mL, reflecting the onset of rapid dissolution of $\text{CaO}/\text{Ca}(\text{OH})_2$ and the acceleration of acid neutralisation. From 7 to 12 minutes, both samples reach their peak reaction region, but Lime 1 consistently displays higher reactivity values

compared to Lime 2. Lime 1 rises steadily to a maximum of approximately 390 mL at around 11–12 minutes, whereas Lime 2 peaks lower, at around 360–365 mL. This difference in peak volume indicates that Lime 1 contains a higher proportion of reactive CaO or demonstrates better calcination quality. After the peak period, both samples show a slight decline in reactivity between 13 and 16 minutes as the available reactive lime becomes depleted and the reaction approaches completion. Throughout most of the reaction period (7–15 minutes), Lime 1 maintains higher reactivity values compared to Lime 2, demonstrating a stronger, faster, and more sustained reaction. Based on these observations, Lime 1 is conclusively the more reactive material, exhibiting greater acid consumption and a more pronounced reaction profile, which are indicative of higher lime purity and better reactivity characteristics under HCl titration conditions.

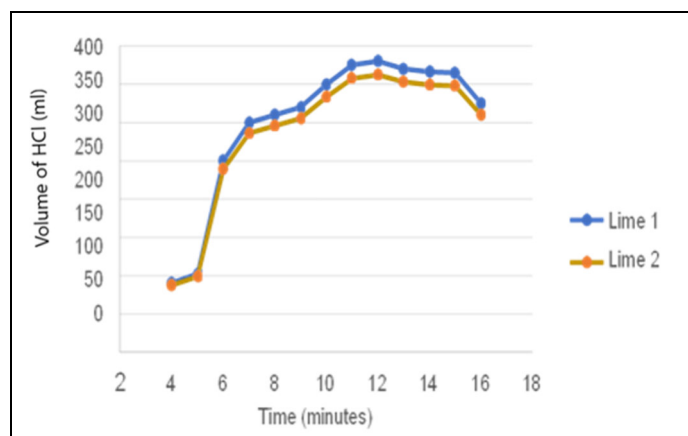
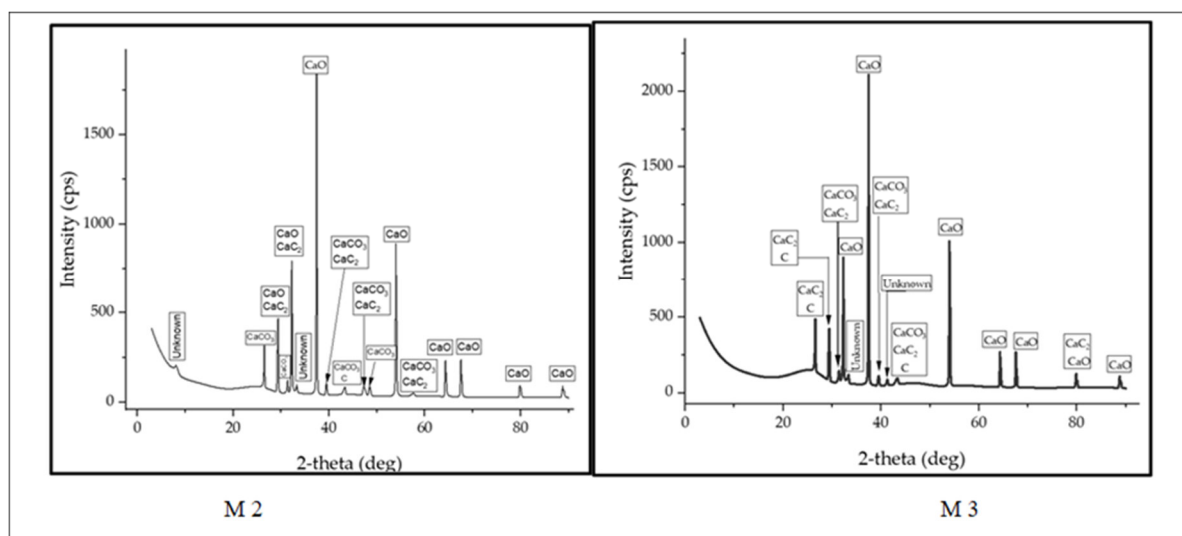


Figure 2 Lime reactivity versus time

3.3 Phases evolution at different temperatures

Figure 3 depicts different phases that formed at 1500°C. the XRD peaks associated with these Ca-silicate phases are stronger at 1500°C within the XRD patterns for M2 and M3, confirming the continuous consumption of free CaO into stable silicate structures. At the same time, high-temperature silica polymorphs such as cristobalite or tridymite appear as quartz transforms, reflecting that silica from ash is chemically reactive at elevated temperatures rather than inert; these transitions are visible in the 1500 °C XRD patterns for M2 and M3. Where the ash contains notable Al₂O₃, calcium aluminates such as CaAl₂O₄ and Ca₃Al₂O₆ also form and appear within the high-temperature XRD patterns, again reducing the pool of available CaO for carbide formation.



Figures 3 XRD results at 1500 °C

From **Figure 3** XRD at 1500 °C results show that in M2 and M3 CaC_2 peaks were present although disseminated. However, some CaCO_3 were still present although the temperature was above its decomposition temperature. This might be attributed to layer at the bottom of the crucible with some CO_2 unable to escape. The presence of silica (SiO_2) and high ash content has several important implications for the CaC_2 production process. First, the formation of calcium-silicates such as CaSiO_3 and Ca_2SiO_4 consumes free CaO that would otherwise react with carbon to form CaC_2 , thereby reducing the maximum theoretical carbide yield; thus, greater silica from coal ash or impure lime results in greater sequestration of reactive CaO into inert silicates.

4. CONCLUSION

The current research focused on a review on calcium carbide production using low-rank coal as reductant. It was found that because carbon source is paramount, Coal 1 exhibited more vitrinite content compared to coal 2 while lime 1 was found highly reactive as opposed to lime 2. However, although CaC_2 formed, SiO_2 has limited CaC_2 formation therefore needs additional lime as a flux. M1 set up is expected to produce a better CaC_2 product with temperature increase. Results obtained have confirmed that Low-Rank coal could be efficiently used for CaC_2 production but should be well selected or else expect for more lime consumption and high slag formation.

ACKNOWLEDGEMENTS

Authors are thankful to the company that provided coal samples that allowed the investigation to go ahead and thank the assistance of lab technicians at the university of Johannesburg.

REFERENCES

- [1] MCCAFFREY, M., KADAR, L., DONG, J., WASMUND, B., ROBINSON, S., & WHARTON, D. (n.d.). *Production Technologies and Operation a 90 mw calcium carbide furnace-process and electrical scale-up*.
- [2] MU, J. J., & HARD, R. A. (1987). A Rotary Kiln Process for Making Calcium Carbide. In *Ind. Eng. Chem.*
- [3] WANG, Q., LI, S., GENG, S., & JIANG, Z. (2021). The single-particle model of calcium carbide production and strengthening mechanism of the novel pelletizing process. *Kexue Tongbao/Chinese Science Bulletin*, vol. 66, no. 21, pp. 2766–2774. <https://doi.org/10.1360/TB-2020-1699>
- [4] MA, S., LU, S., MA, H., LI, R., XU, C., CHEN, M., & ZHANG, H. (2022). Energy and exergy analysis of a new calcium carbide production process. *Fuel Processing Technology*, 226. <https://doi.org/10.1016/j.fuproc.2021.107070>
- [5] HUO, H., LIU, X., WEN, Z., LOU, G., DOU, R., SU, F., ZHOU, W., & JIANG, Z. (2021). Case study of a novel low rank coal to calcium carbide process based on techno-economic assessment. *Energy*, 228. <https://doi.org/10.1016/j.energy.2021.120566>.
- [6] JIANG, P., ZHAO, G., ZHANG, H., JI, T., MU, L., LU, X., & ZHU, J. (2024). Towards carbon neutrality of calcium carbide-based acetylene production with sustainable biomass resources. *Green Energy and Environment*, vol. 9, no. 6, pp. 1068–1078. <https://doi.org/10.1016/j.gee.2022.12.004>
- [7] DENG, E., & BAIYEGUNHI, C. (2021). Maceral types and quality of coal in the tuli coalfield: A case study of coal in the madzaringwe formation in the Vele Colliery, Limpopo Province, South Africa. *Applied Sciences (Switzerland)*, vol. 11, no. 5, pp. 1–15. <https://doi.org/10.3390/app11052179>
- [8] XIAOMIN, Y., JINGSONG, W., XUEFENG, S., ZEYI, J., & QINGGUO, X. (2022). Comparison of new two-step calcium carbide production process and traditional production process using numerical simulation of heat transfer and chemical reaction. *Chemical Engineering Research and Design*, vol. 187, pp. 516–528.
- [9] JI, L., LIU, Q., & LIU, Z. (2014). Thermodynamic analysis of calcium carbide production. *Industrial and Engineering Chemistry Research*, vol. 53, no. 6, pp. 2537–2543