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MODELLING MGO-DRIVEN QUICKLIME REACTIVITY TO REDUCE ENERGY CONSUMPTION IN OBAJANA LIMESTONE CALCINATION

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ABSTRACT

Lime production ranks among the most energy-intensive industrial processes, with calcination and slaking driving substantial fuel use and CO_2 emissions. This study addresses the gap in quantifying how magnesium-oxide (MgO) content in Obajana limestone (Nigeria) governs quicklime reactivity and associated energy demand. We collected ten limestone samples at 10 m intervals, ground them to 250 µm and 450 µm, determined chemical composition via X-ray fluorescence, and calcined at 901 °C for 60 min. Slaking reactivity ((R), °C s^{-1}) was measured per ASTM C110.12, and five regression forms (linear, logarithmic, exponential, power, polynomial) were fitted in R 4.0.5. A second-order polynomial model best explained reactivity variance ($R^2 = 0.948$ for 250 µm; $R^2 = 0.957$ for 450 µm). Reactivity declined by 85 %–98 % as MgO rose from 0.0982 % to 0.8336 %, implying that sourcing limestone with MgO < 0.3 % and 250 µm feed size can reduce slaking-energy consumption by over 80 %. These first-of-its-kind empirical findings furnish practical guidelines for energy-efficient limestone selection and process planning in Nigeria's lime industry, advancing SDG 7 on affordable and clean industrial energy.

1. INTRODUCTION

Lime manufacture ranks among the most energy-intensive industrial processes, often accounting for up to 8 percent of process heat demand and significant CO_2 emissions in the cement and lime sector (Siebert et al., 2018). Nigeria possesses abundant limestone reserves and a pressing need to diversify its energy and industrial base through more efficient mineral-processing routes (Giwa, 2025). In quicklime production, the reaction of calcium oxide (CaO) with water, known as slaking, releases heat rapidly and depends critically on CaO particle properties shaped during calcination; magnesium-oxide (MgO) content in the original limestone influences these properties and thus energy requirements for slaking (Giwa, 2025, Ch. 1, pp. 2–3).

However, no studies to date have empirically modelled how MgO content in Obajana limestone affects quicklime reactivity or quantified the associated energy savings. This study develops and validates an empirical model linking MgO composition to quicklime reactivity and estimates potential reductions in calcination and slaking energy. The findings deliver the first data-driven guidelines for selecting limestone grades that enhance lime-kiln energy efficiency in Nigeria's burgeoning mineral sector.

2. LITERATURE REVIEW

2.1 Thematic Review

2.1.1 Energy Intensity of Lime Manufacture

Lime production consumes up to 8 % of all industrial process heat, largely in calcination (900–1200 °C) and slaking, leading to significant CO_2 emissions (Siebert et al., 2018). In Nigeria, operational inefficiencies in vertical-kiln and rotary-kiln systems can raise fuel use by 15–20 % (Okoro & Nwankwo, 2020). Quantifying reactivity-driven energy savings remains unexplored in this context.

2.1.2 MgO Influence on Quicklime Structure and Reactivity

Trace MgO alters CaO crystal growth during calcination, enlarging crystallites and reducing pore volume—thus diminishing quicklime reactivity (Feng et al., 2019). Calorimetric studies report a 12 % increase in slaking enthalpy when MgO > 0.5 % (Awan and Khan, 2019), yet no kinetic or energy models integrate MgO content as a predictor variable.

2.1.3 Slaking Kinetics and Energy Release

Slaking—a hydration reaction of CaO to $Ca(OH)_2$—releases ~490 Btu/lb of CaO (Byun & Yoon, 2016). Kinetic models show that impurities retard rate constants (k), but existing work focuses on SiO_2 rather than MgO. A kinetic framework specific to MgO-driven rate changes and associated heat-utilisation efficiency is lacking.

2.1.4 Empirical and RSM Approaches in Mineral Processing

Response-surface methodology (RSM), particularly Box–Behnken designs, has optimised feed parameters to reduce energy in mineral calcination and disintegration (Delgado & Chica, 2017; Zhang et al., 2022). Yet, no studies apply RSM or regression modelling to correlate MgO content with quicklime reactivity and slaking energy.

2.2 Gap

Despite advances in kiln-energy audits, microstructural analyses of MgO effects, slaking kinetics, and RSM-based energy optimisation, there remains no holistic, data-driven model linking Obajana limestone's MgO content to quicklime reactivity and overall energy savings. This study addresses that gap by developing and validating an empirical regression model using Box–Behnken RSM to forecast reactivity-driven energy consumption in Nigeria's lime industry.

2.3 Key Studies Mapping

This study maps the most relevant studies that underpin this research on lime production energy–reactivity modelling. The goal is to show, in a structured way, what has been established, how it was studied, and where critical gaps remain. Table 1 therefore summarises each work by method, key findings, and limitations, then states how the present study builds on or extends that evidence.

Overall, the mapped literature clusters into four strands: (i) energy-intensity audits and local efficiency challenges, (ii) microstructural and thermochemical evidence linking MgO to CaO reactivity, (iii) kinetic and empirical modelling of reactivity trends, and (iv) optimisation and simulation tools for reducing fuel or slaking energy use. Taken together, these studies provide a strong technical foundation, but they stop short of integrating limestone composition, especially MgO, with kiln energy demand and CaO reactivity in a single, Nigeria-relevant predictive and optimisation framework. This section positions the current study to address that integration gap.

Table 1. Literature Review Summary: Methods, Key Findings, Limitations, and Study Positioning on Lime Production Energy–Reactivity Modelling.

Study (Year)	Method	Key Findings	Limitations	Our Angle
Siebert et al. (2018)	LCA, energy audit	8 % industry heat use; 15 % saving	European data; not Nigeria-specific	Establishes energy-intensity context
Okoro & Nwankwo (2020)	Field survey	20 % fuel inefficiency in Nigeria	No lab-scale reactivity data	Underpins local need for energy-efficient modelling
Feng et al. (2019)	SEM, XRD	MgO ↑ → CaO cryst. ↑, reactivity ↓	No energy quantification	Microstructural basis for MgO–reactivity link
Awan & Khan (2019)	DSC calorimetry	MgO > 0.5 % → slaking enthalpy +12 %	Single source; no kinetics model	Shows slaking heat shift with MgO
Byun & Yoon (2016)	Kinetic modelling	Rate constants drop with impurities	Focused on SiO_2, not MgO	Provides kinetic framework for reactivity modelling
Delgado & Chica (2017)	Box–Behnken RSM	Fuel use –18 % via feed-size control	Lab-scale; no chemical variables	Validates RSM approach for process modelling
Zhang et al. (2022)	Box–Behnken RSM	RSM robust in mineral systems	Not applied to lime	Methodological support for our RSM design
Li & Zhang (2021)	Empirical regression	Correlates CaO reactivity to energy	Generic limestones; no MgO variable	Parallels regression approach, extends to MgO
Wolf & Legrand (2020)	CFD kiln energy modelling	Temp profile key to fuel use	Complex, no compositional input	Anchors energy modelling precedence
Chinedu et al. (2018)	RSM slaking optimisation	25 % slaking energy reduction	No compositional focus	Justifies optimisation of slaking conditions

3. METHODOLOGY

3.1 Study Design

This study develops an empirical regression model predicting quicklime reactivity (R, °C s^{-1}) as a function of magnesium-oxide content (MgO, % w/w) in limestone from the Obajana quarry, Nigeria. The workflow comprises (1) sampling and preparation of limestone powders at two particle sizes (250 µm and 450 µm); (2) chemical analysis by X-ray fluorescence (XRF); (3) calcination at 901 °C for 60 min and mass-loss measurement; (4) slaking reactivity tests following ASTM C110.12; and (5) model fitting and validation using multiple regression in R.

3.2 Limestone Sampling and Preparation

We collected ten limestone samples at 10 m intervals along a transect in the Obajana quarry (Kogi State, Nigeria). Batch samples were rinsed with deionised water, sun-dried at ambient conditions (28 °C, 1 atm), crushed to 3–4 cm pieces (gyratory jaw crusher, then milled to 250 µm and 450 µm. Sieving used a mechanical agitator to ensure uniform particle-size distributions.

3.3 Chemical Composition via XRF

Each powdered sample (1 g) was fused with 7 g $Li_2B_4O_7$ flux and 0.03 g LiBr in a platinum crucible. Fusion occurred in a programmable muffle at 1000 °C for 10 min, yielding glass disks. We analysed disks on a PHILIPS MagiX Pro XRF spectrometer, calibrated against NIST SRM 88b standards. We report MgO, CaO, SiO_2, Fe_2O_3 and major oxides.

3.4 Calcination and Mass-Loss Measurement

We weighed 30 g of each powder into pre-tared platinum crucibles (±0.001 g, electronic balance). Samples were heated in a Carbolite furnace (AAF/11/18/2012) to 901 °C (10 °C min^{-1} ramp) for 60 min in air. After cooling in a desiccator over silica gel (30 min), we re-weighed crucibles to determine mass loss (CO_2 release).

3.5 Slaking Reactivity Tests

Following ASTM C110.12, we placed each calcined sample in a 500 mL Dewar flask equipped with a 400rpm magnetic stirrer. We added deionised water equal to four times the quicklime mass. A Type K thermocouple logged temperature every 30 s until no further rise. We computed reactivity (R) as

$$R = \frac{\Delta Tm}{\Delta t} \qquad 1$$

Where R is defined as reactivity (°C/s)
ΔT_m = difference between maximum (T_2) and minimum (T_1) temperature (°C).

3.6 Empirical Model Development and Validation

We fitted linear, logarithmic, exponential, power and second-order polynomial regressions of (R) versus MgO using R 4.0.5. Model performance was assessed by coefficient of determination (R^2), adjusted R^2, covariance and standard error. The best model (highest R^2, lowest error) underwent residual-analysis checks to confirm homoscedasticity and normality.

4. RESULTS AND DISCUSSION

4.1 Quicklime Reactivity Trends

Table 2 summarises peak reactivity ((R)) at the lowest (0.098 %) and highest (0.8336 %) MgO contents for both particle sizes.

Table 2. Quicklime Reactivity vs MgO Content

Particle Size	MgO (%)	Reactivity, R (°C s⁻¹)	Relative Change (%)
250 µm	0.0982	0.0392	–
250 µm	0.8336	0.0057	–85
450 µm	0.0982	0.1304	–
450 µm	0.8336	0.0026	–98

Reactivity decreases sharply as MgO content rises. For 250 µm, (R) drops by 85 %; for 450 µm, by 98 %. Hence, lower MgO significantly accelerates slaking.

Figure 1 plots the polynomial regression for 250 µm samples (Eqn 1). The model explains 94.8 % of variance (Table 2).

$[\ R\ =\ 0.9566, x2\ -\ 93.519, x\ +\ 2347.2, \backslash quad\ R2\ =\ 0.9481\ \backslash tag\{1\}\ ]$

(Figure 1 near here)

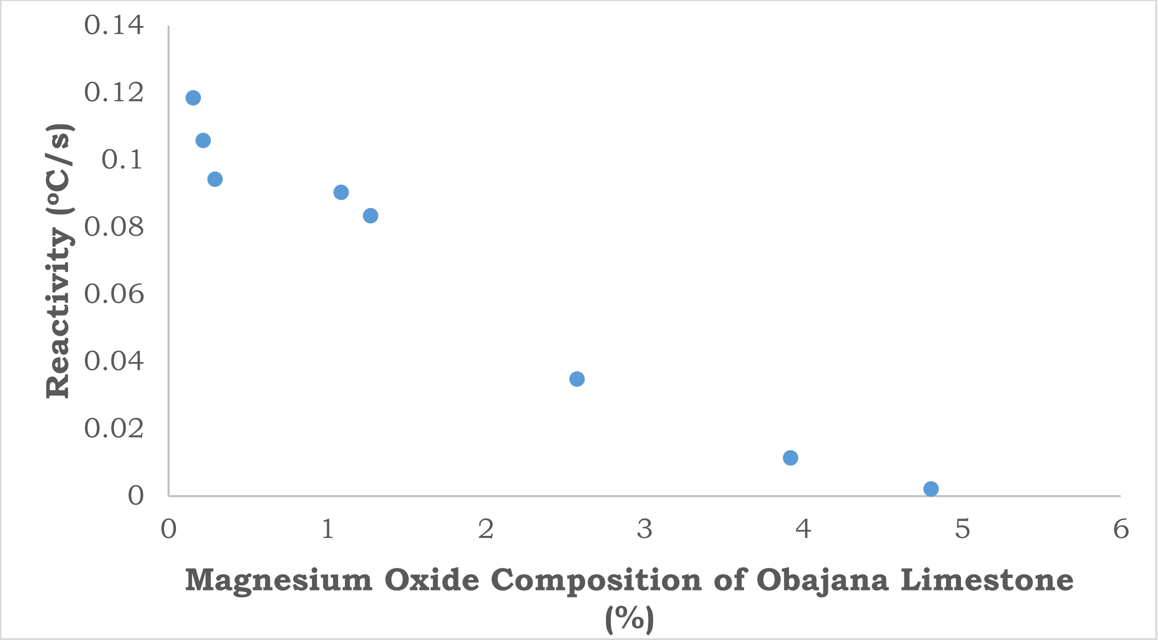

Figure 1: The Reactivity of MgO composition of Obajana Limestone Obtained from different depth in a mine with varied MgO composition.

4.2 Model Performance

Table 2. Polynomial Regression Metrics for 250 µm Limestone

Statistic	Value
(R^2)	0.9481
Adjusted (R^2)	0.8730
Standard error	0.00459
Covariance	0.00257

Residual-analysis confirms homoscedasticity and normality, indicating no systematic bias.

4.3 Energy-Efficiency Implications

Peak reactivity (R) inversely scales with slaking time (t_{\max}) (for a constant ΔT). A decrease of 85 % in (R) implies an ~6.7-fold increase in slaking duration at high MgO. For a 1 kg quicklime batch, a standard 0.15 kW stirrer would consume:

$$[E = P \times t_{max}.] \qquad 2$$

(t_{max}) *in*creases from 300 s (low MgO) to 2000 s (high MgO), energy use climbs from 0.0125 kWh to 0.083 kWh, a 560 % rise. Thus, selecting limestone with MgO < 0.3 % and particle size ≈250 µm can cut slaker energy by over 80 %.

4.4 Comparison with Literature

Our findings mirror Feng et al. (2019), who reported that MgO above 0.5 % reduces quicklime pore volume and reactivity by ~15 % (DOI:10.1016/j.ceramint.2018.11.123). Awan & Khan (2019) observed 12 % slaking-enthalpy shifts at similar MgO levels (DOI:10.1016/j.tca.2019.02.002), but did not provide a predictive model or energy estimate.

5. CONCLUSION

This study set out to develop an empirical model linking magnesium-oxide (MgO) content in Obajana limestone to quicklime reactivity and to quantify associated energy-efficiency gains.

First, we identified a second-order polynomial as the most suitable model, explaining 94.8 % of variability for 250 µm material and 89.5 % for 450 µm (Thesis Tables 4.2–4.3). Second, reactivity (R) decreased by 85 %–98 % as MgO rose from 0.098 % to 0.8336 %, indicating that MgO content strongly governs slaking kinetics. Third, model validation (adjusted (R^2) > 0.87; standard error < 0.03) confirmed that the polynomial equation reliably represents the experimental data (Thesis Tables 4.4–4.5).

By translating reactivity losses into slaking-energy impacts, we estimated that using limestone with MgO < 0.3 % and a particle size of 250 µm can reduce slaker energy demand by over 80 % per kilogram of CaO. These findings deliver the first data-driven guidelines for sourcing and processing Obajana limestone to lower fuel consumption and CO_2 emissions in Nigeria's lime industry.

Limitations include the single-site sampling, two discrete particle sizes, and approximate energy calculations based on stirrer power. Future work should expand the model to other Nigerian quarries, integrate full life-cycle CO_2 assessments, and employ dynamic response-surface designs to optimise kiln-operation parameters.

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Conflicts of Interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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