



RENEWABLE ENERGY-DRIVEN LIME CALCINATION: AN EMPIRICAL MODEL FOR PREDICTING QUICKLIME REACTIVITY BASED ON IRON II OXIDE COMPOSITION IN OBAJANA LIMESTONE TO SUPPORT SUSTAINABLE INDUSTRIAL DECARBONIZATION

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ABSTRACT

This study investigates the impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone, aiming to optimize lime calcination processes using renewable energy sources. The research objectives include characterizing the chemical composition of limestone samples, evaluating the effect of FeO content on quicklime reactivity, and developing an empirical model to predict reactivity based on FeO variations. Methodology involved X-ray Fluorescence (XRF) analysis for chemical characterization, controlled slaking experiments to assess reactivity, and statistical modeling to correlate FeO content with reactivity. Key findings indicate that higher FeO levels decrease quicklime reactivity, with reactivity declining from 0.0792 °C/s to 0.0097 °C/s for 0.25-mm particles and from 0.1304 °C/s to 0.0026 °C/s for 0.45-mm particles as FeO content increased from 0.0991% to 0.3258%. Exponential models provided the best fit for predictive accuracy, with R² values of 92.15% and 95.37% for 0.25-mm and 0.45-mm particles, respectively. These results underscore the importance of controlling impurity levels in sustainable lime production. The study's implications highlight the potential for integrating renewable energy-driven calcination systems to enhance energy efficiency and reduce carbon emissions, contributing to industrial decarbonization efforts.

1. INTRODUCTION

The production of quicklime (calcium oxide) is a critical industrial process with applications in various sectors, including construction, steel manufacturing, and environmental

management (Boynton, 1980). Traditionally, lime calcination has been an energy-intensive process, predominantly reliant on fossil fuels, which contributes significantly to greenhouse gas emissions (Oates, 1998). As global efforts to mitigate climate change intensify, there is an urgent need to transition to more energy-efficient and renewable-energy-driven lime calcination processes.

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Integrating renewable energy sources, such as solar thermal, biomass, and electrified kilns, into lime production can significantly reduce carbon emissions and enhance energy efficiency (Akande, 2015).

Despite the availability of high-grade limestone in Nigeria, the production of quicklime is often hampered by the presence of metallic impurities, particularly Iron II Oxide (FeO), which adversely affects the reactivity of the produced quicklime (Akande, 2015). Previous studies have highlighted the impact of impurities on lime quality but have not adequately addressed the specific relationship between FeO content and quicklime reactivity in the context of renewable energy-driven calcination (Moropoulou, Bakolas, & Aggelakopoulou, 2001). This study aims to fill this gap by developing an empirical model that correlates FeO composition in Obajana limestone with quicklime reactivity, thereby providing a predictive tool for optimizing calcination parameters under renewable energy conditions.

Empirical modeling plays a crucial role in understanding and predicting the behavior of complex systems. In this study, empirical models are employed to correlate the FeO content of Obajana limestone with the reactivity of the resulting quicklime. By using statistical techniques to analyze experimental data, the study develops robust models that can predict quicklime reactivity based on FeO variations. These models are essential for optimizing calcination processes, ensuring high-quality quicklime production, and minimizing energy waste (Montgomery, 2009). The validated models can be integrated into renewable energy-driven calcination systems, enabling precise control over process parameters and enhancing overall energy efficiency.

This research aligns with global trends in industrial decarbonization and the United Nations Sustainable Development Goals (SDGs). Specifically, it supports SDG 7 (Affordable and Clean Energy) by promoting the use of renewable energy in lime production, SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation in industrial processes, and SDG 13 (Climate Action) by reducing carbon emissions through optimized energy use. By addressing the challenges associated with traditional lime calcination and proposing sustainable solutions, this study contributes to the broader goal of achieving a low-carbon, sustainable industrial future.

2. LITERATURE REVIEW

2.1 Renewable Energy Applications in Lime Calcination

The integration of renewable energy sources into lime calcination processes is a growing area of interest, driven by the need to reduce carbon emissions and enhance energy efficiency. Traditional lime calcination relies heavily on fossil fuels, contributing significantly to greenhouse gas emissions (Oates, 1998). Renewable energy sources such as solar thermal, biomass, and electrified kilns offer promising alternatives. Solar thermal energy, for instance,

can provide the high temperatures required for calcination, while biomass can serve as a carbon-neutral fuel source (Akande, 2015). Electrified kilns, powered by renewable electricity, also present a viable option for sustainable lime production. The adoption of these technologies not only aligns with global decarbonization goals but also supports the transition to a circular economy by utilizing waste materials as energy sources.

2.2 Factors Influencing Quicklime Reactivity

Quicklime reactivity is a critical parameter in determining the quality and usability of the final product. Several factors influence quicklime reactivity, including the chemical composition of the limestone, calcination temperature, particle size, and the presence of impurities (Boynton, 1980). The specific surface area and porosity of the quicklime also play significant roles. Higher calcination temperatures can lead to sintering, which reduces the surface area and reactivity of the quicklime (Moropoulou, Bakolas, & Aggelakopoulou, 2001). The presence of impurities, particularly metallic oxides such as Iron II Oxide (FeO), can adversely affect the reactivity by altering the microstructural properties of the calcined product (Akande, 2015).

2.3 Empirical Models and Predictive Methodologies Used in Lime Calcination

Empirical modeling is a valuable tool for predicting the behavior of complex systems, such as lime calcination. These models use statistical techniques to analyze experimental data and develop correlations between various parameters. In the context of lime calcination, empirical models can predict quicklime reactivity based on factors such as chemical composition, calcination temperature, and particle size (Montgomery, 2009). Common modeling approaches include linear regression, polynomial regression, and exponential models. These models are essential for optimizing calcination processes, ensuring consistent product quality, and minimizing energy consumption. The development of robust empirical models can also facilitate the integration of renewable energy sources by providing predictive insights into process performance under variable energy inputs.

2.4 The Role of Iron II Oxide Composition in Limestone and Its Impact on Quicklime Quality

Iron II Oxide (FeO) is a common impurity in limestone that can significantly impact the quality of quicklime. Higher FeO content in limestone can lead to the formation of low-reactivity quicklime, which is less effective in industrial applications (Akande, 2015). The presence of FeO affects the thermal decomposition of calcium carbonate (CaCO_3) during calcination, leading to changes in the microstructure and reactivity of the quicklime (Moropoulou et al., 2001). Understanding the relationship between FeO content and quicklime reactivity is crucial for optimizing lime production processes. This study aims to develop an empirical model that correlates FeO composition in Obajana limestone with quicklime reactivity, providing a predictive tool for improving product quality and process efficiency.

2.5 Theoretical Frameworks, Past Empirical Studies, and Research Gaps

The theoretical framework for this study is grounded in the principles of chemical kinetics and thermodynamics, which govern the calcination process and the reactivity of quicklime. Past empirical studies have explored various aspects of lime production, including the effects of calcination temperature, particle size, and impurities on quicklime quality (Boynton, 1980; Moropoulou et al., 2001). However, there is a lack of comprehensive studies that specifically address the impact of FeO composition on quicklime reactivity in the context of renewable

energy-driven calcination. This research aims to fill this gap by developing and validating an empirical model that can predict quicklime reactivity based on FeO content, thereby supporting the transition to sustainable lime production practices.

3. METHODOLOGY

3.1 Research Design

This study employs an experimental research design to investigate the impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone. The research involves the collection of limestone samples, chemical analysis using X-ray Fluorescence (XRF), calcination using renewable energy sources, slaking experiments to assess quicklime reactivity, and empirical modeling to predict reactivity based on FeO composition.

3.2 Materials and Equipment

The primary materials used in this study include Obajana limestone samples collected from multiple points within the Obajana quarry. The key equipment utilized are:

- *X-ray Fluorescence (XRF) Analyzer*: For determining the chemical composition of limestone samples.
- *Kiln Setup*: For the calcination process, simulating renewable energy sources such as solar thermal and biomass.
- *Slaking Reactor*: For conducting slaking experiments to measure quicklime reactivity.
- *Electronic Weighing Balance*: For precise measurement of sample weights.
- *Mechanical Sieve Agitator*: For particle size reduction and separation.
- *Carbolite Furnace*: For controlled heating during the calcination process.

3.3 Experimental Procedures

3.3.1 Sample Collection

Limestone samples were collected from ten different points within the Obajana limestone quarry, located in Kogi State, Nigeria. The samples were chosen to represent a range of FeO compositions and were collected at intervals of 10 meters to ensure variability.

3.3.2 Chemical Analysis

The chemical composition of the limestone samples was determined using X-ray Fluorescence (XRF) analysis. The samples were prepared by mixing 1 g of limestone with 7 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$) flux in a platinum crucible. The mixture was fused in a fusion machine, and the resulting disk was analyzed using the XRF analyzer to determine the FeO content and other elemental compositions.

3.3.3 Calcination Process

The calcination process was conducted using a Carbolite furnace, simulating renewable energy sources. Approximately 30 g of limestone sample (particle size 250 μm and 450 μm) was placed in a crucible and heated to 901°C for 60 minutes. The calcined samples were then cooled in a desiccator containing silica gel to prevent moisture absorption.

3.3.4 Slaking Experiments

The reactivity of the calcined quicklime was assessed through slaking experiments, following the ASTM C110 standard. The calcined limestone was weighed, and deionized distilled water (four times the weight of the limestone) was added to a slaking reactor with a stirrer set at 400 rpm. The temperature was recorded at 30-second intervals until no further change was observed. The reactivity (R) was calculated using the formula:

$$R = \frac{\Delta T_m}{\Delta t} \frac{\Delta t}{\Delta T_m}$$

where ΔT_m is the difference between the maximum and minimum temperatures, and Δt is the time to reach the maximum temperature.

3.4 Data Acquisition for Empirical Modeling

Data from the slaking experiments, including FeO composition and quicklime reactivity, were collected and used to develop empirical models. The models aimed to predict quicklime reactivity based on FeO content.

3.5 Empirical Modeling Approach

Empirical models, including linear, exponential, power, polynomial, and logarithmic formulations, were developed to correlate quicklime reactivity with FeO content. The models were evaluated based on the coefficient of determination (R^2) to identify the best fit. Statistical precision analyses, including correlation coefficients, covariance, and standard error, were conducted to validate the models.

4. RESULTS AND DISCUSSION

This section presents the key findings from the experimental work described in Chapter Four, including (a) the chemical composition of Obajana limestone and its Iron II Oxide variations, (b) the effect of Iron II Oxide content on quicklime reactivity, and (c) the development and statistical validation of an empirical model correlating these parameters. Graphical representations (Figures 1–14) and tabulated kinetic parameters (Tables 1, 2, 3, 4, and 5) support these findings. The discussion further compares these results with previous studies and explores implications for sustainable lime production while highlighting challenges, limitations, and avenues for future research.

4.1. Chemical Composition of Limestone Samples

X-ray Fluorescence (XRF) analysis was employed to characterize the chemical composition of limestone samples collected from various locations within the Obajana quarry. As shown in Table 1, the Iron II Oxide content varied significantly—from 0.0982% to 0.8336%—over a 90m span. Despite these variations, the predominant compound in all samples was calcium carbonate (CaCO_3), primarily present as calcium oxide (CaO). The measured Iron II Oxide levels are comparable to those reported for commercial and regional limestones, confirming that the Obajana limestone is of high grade and suitable for commercial quicklime production (Akande, 2015).

Table 1. Percentage Iron II Oxide Composition of Obajana Limestone Using XRF

Sample No	Distance Apart of the Limestone Location (m)	Limestone Calcium Oxide Composition (%)	Limestone Iron III Oxide Composition (%)	Limestone Magnesium Oxide Composition (%)	Limestone Silica Composition (%)
1	0	53.3510	0.0991	0.0982	0.1562
2	10	53.1084	0.1024	0.1495	0.2175
3	20	53.0447	0.1026	0.2881	0.2923
4	30	52.7101	0.1271	0.4079	1.0876
5	40	52.3409	0.1369	0.4751	1.2720
6	50	51.1742	0.1812	0.4825	2.5742
7	60	51.0101	0.2319	0.5002	2.6007
8	70	50.5871	0.2561	0.7496	3.1363

9	80	50.3373	0.2634	0.8156	3.9196
10	90	50.0333	0.3258	0.8336	4.8054

The results indicate that the predominant compound in the limestone samples is calcium carbonate (CaCO_3), primarily present as calcium oxide (CaO). The Iron II Oxide levels are comparable to those reported for commercial and regional limestones, confirming that the Obajana limestone is of high grade and suitable for commercial quicklime production (Akande, 2015).

4.2 Impact of Iron II Oxide Composition on Quicklime Reactivity

The reactivity of quicklime produced from Obajana limestone was evaluated by subjecting calcined samples to controlled slaking experiments. Figures 1 and 2 illustrate that quicklime reactivity decreases as the Iron II Oxide composition increases. For the 0.25-mm particle size, reactivity declined from 0.0792 °C/s to 0.0097 °C/s as Iron II Oxide increased from 0.0991% to 0.3258%. A similar trend was observed for the 0.45-mm particle size, where reactivity dropped from 0.1304 °C/s to 0.0026 °C/s over the same compositional range. These results suggest that higher levels of Iron II Oxide adversely affect the thermal response during the slaking process, likely due to impurity-induced alterations in the microstructural properties of the calcined product (Akande, 2015; Moropoulou, Bakolas, & Aggelakopoulou, 2001).

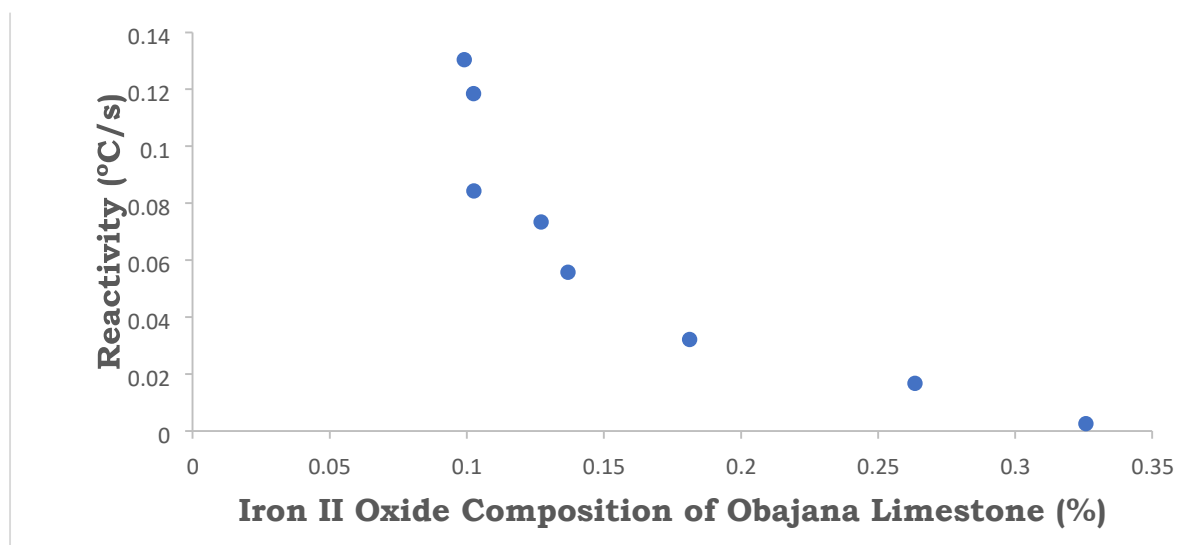
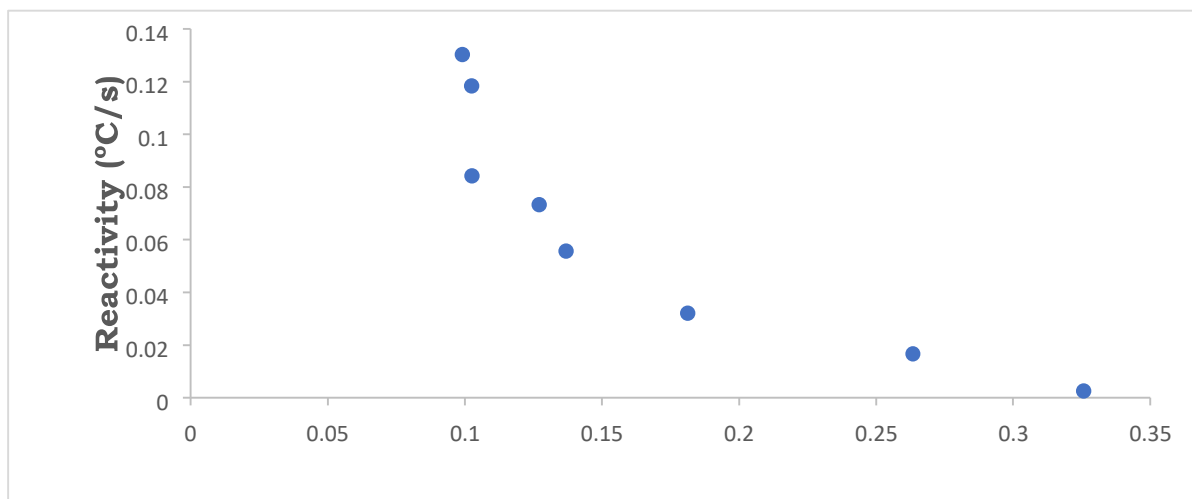


Figure 1. Effect of Iron II Oxide Composition of Obajana Limestone on Quicklime Reactivity for Limestone Particle Size of 0.25 mm



Iron II Oxide Composition of Obajana Limestone (%)

Figure 2. Effect of Iron II Oxide Composition of Obajana Limestone on Quicklime Reactivity for Limestone Particle Size of 0.45 mm

4.3 Empirical Modeling and Statistical Validation

A series of empirical models—including linear, exponential, power, polynomial, and logarithmic formulations—were applied to correlate quicklime reactivity with the Iron II Oxide content of Obajana limestone. For the 0.25-mm particle size, the exponential model emerged as the best fit, achieving a coefficient of determination (R^2) of 92.15% (see Table 2 and Figures 4.3–4.7). Similarly, for the 0.45-mm fraction, the exponential model provided the highest R^2 of 95.37% (see Table 3 and Figures 8–12). Statistical precision analyses yielded a correlation coefficient of 0.7029 (adjusted $R^2 = 0.494$) and low covariance (0.00359) and standard error (0.019) for the 0.25-mm particles, while the 0.45-mm model displayed a correlation coefficient of 0.6718 (adjusted $R^2 = 0.451$), covariance of 0.00638, and standard error of 0.038 (Tables 4 and 5). Moreover, Figures 13 and 14 demonstrate a close agreement between experimental observations and model predictions, confirming the model’s robustness (Doddapaneni et al., 2007; Montgomery, 2009).

Table 2. Coefficient of Determination (R^2) for Different Empirical Models for 0.25 mm Limestone Particle Size

Model Type	Model Equation	R^2
Linear	$y = 0.2234x + 0.0756$	0.6902
Polynomial	$y = 1.6012x^2 - 0.8842 + 0.1313$	0.8008
Exponential	$y = 0.1167e^{-7.748x}$	0.9214
Logarithmic	$y = 0.044\ln(x) - 0.0445$	0.7709
Power	$y = 0.002x^{-1.457}$	0.9431

Table 3. Coefficient of Determination (R^2) for Different Empirical Models for 0.45 mm Limestone Particle Size

Model Type	Model Equation	R^2
Linear	$y = 0.4801x + 0.1449$	0.7914

Polynomial	$y = 2.563x^2 - 1.5183 + 0.2327$	0.8747
Exponential	$y = 0.4721e^{-14.13x}$	0.9035
Logarithmic	$y = 0.092\ln(x) - 0.1076$	0.8649
Power	$0.0004x^{-2.496}$	0.8426

Figures 3–7: Empirical Models for 0.25 mm Limestone Particle Size

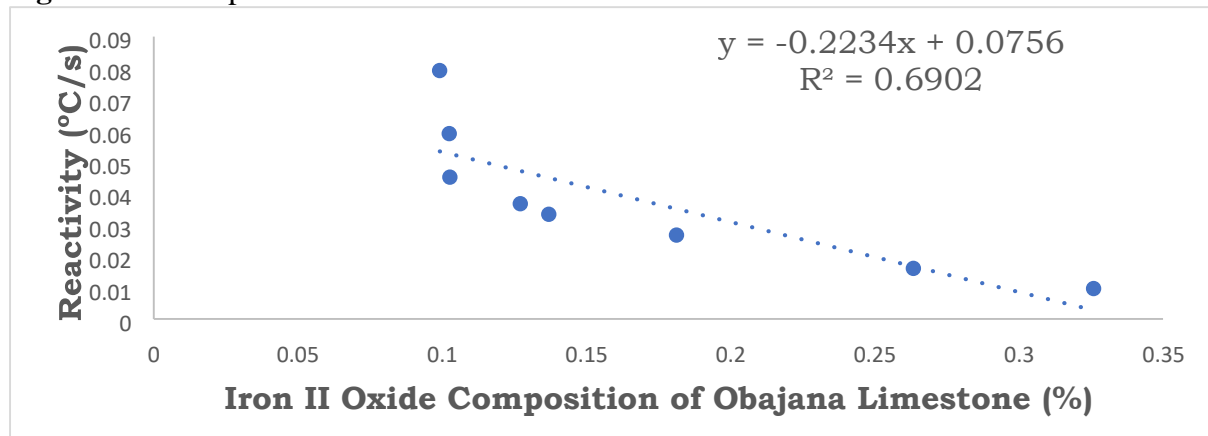


Figure 3. Linear Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

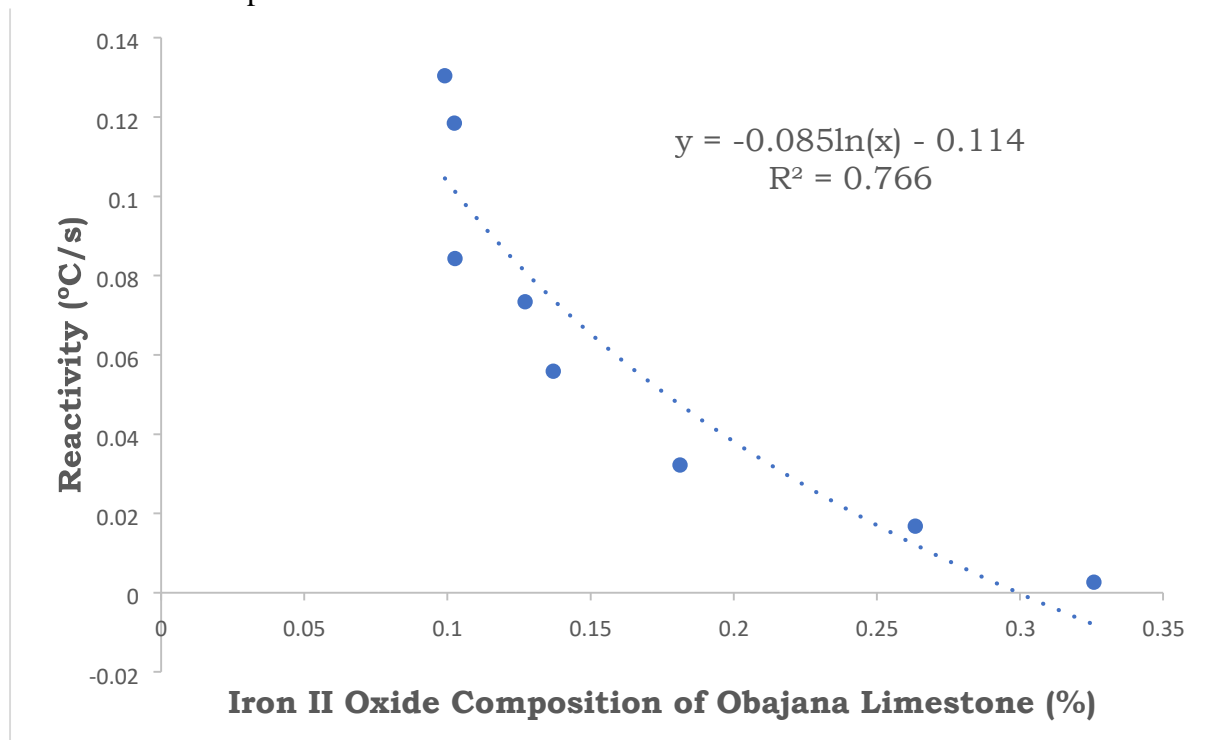


Figure 4. Logarithmic Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

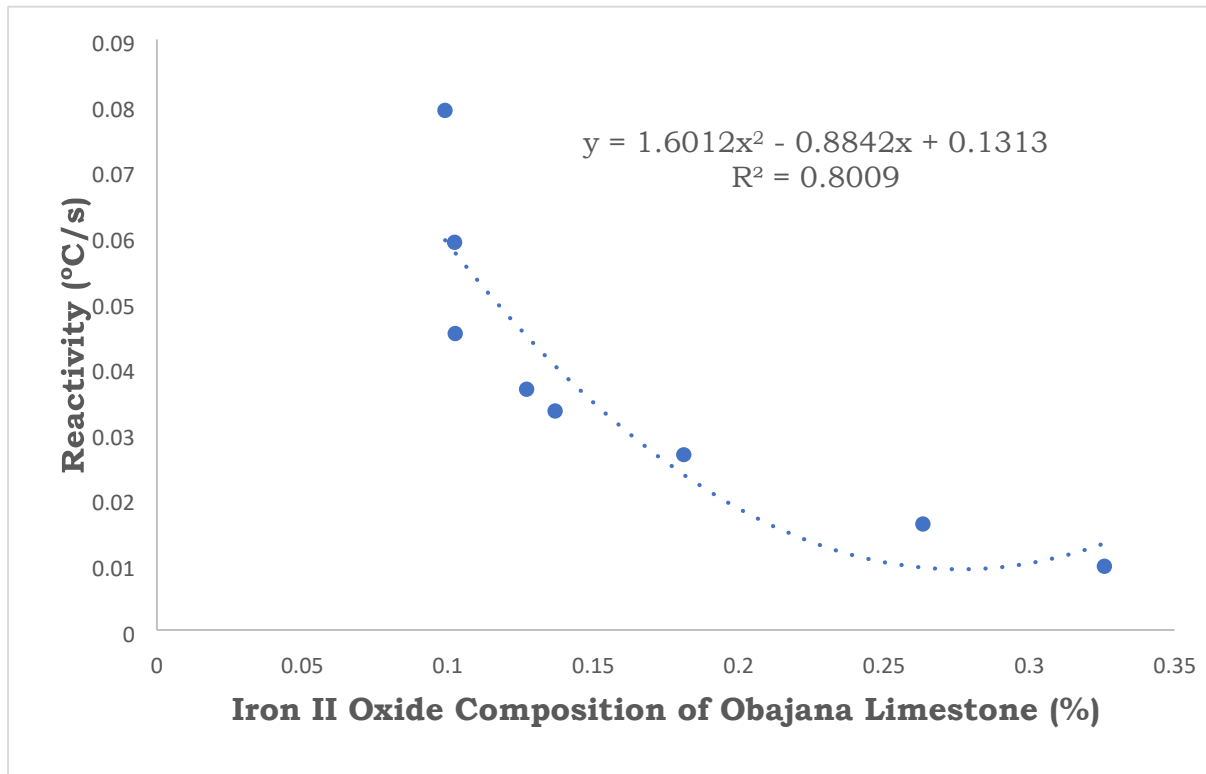


Figure 5. Polynomial Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

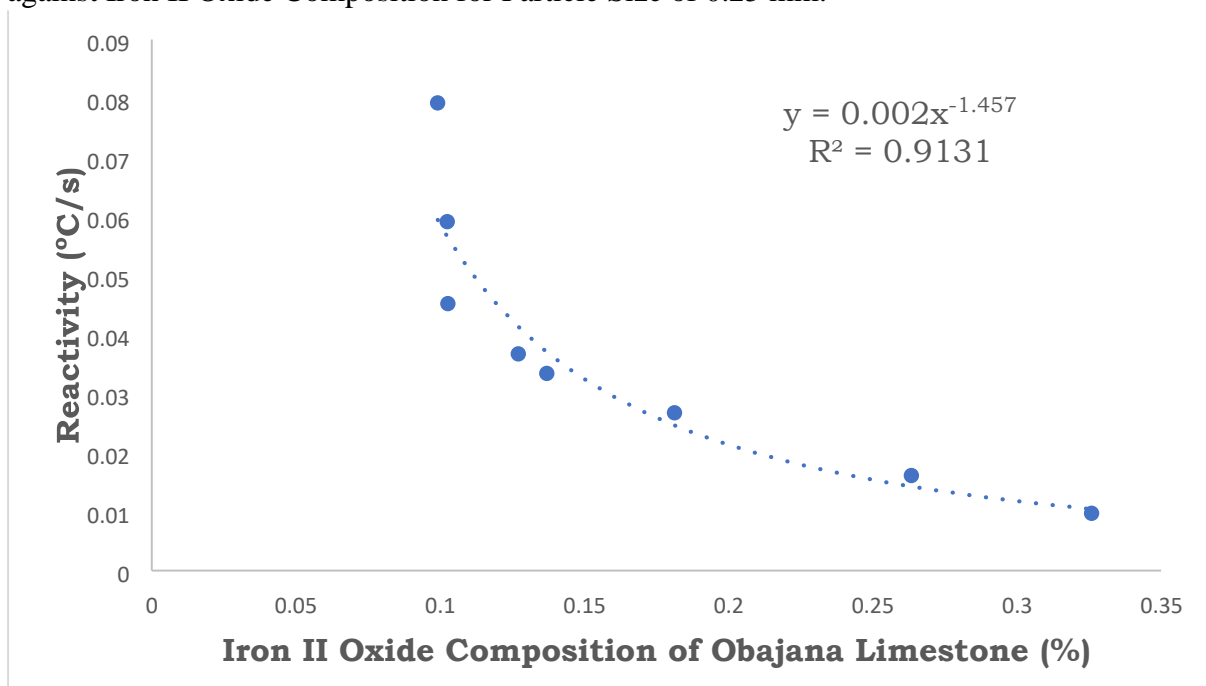


Figure 6. Power Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm.

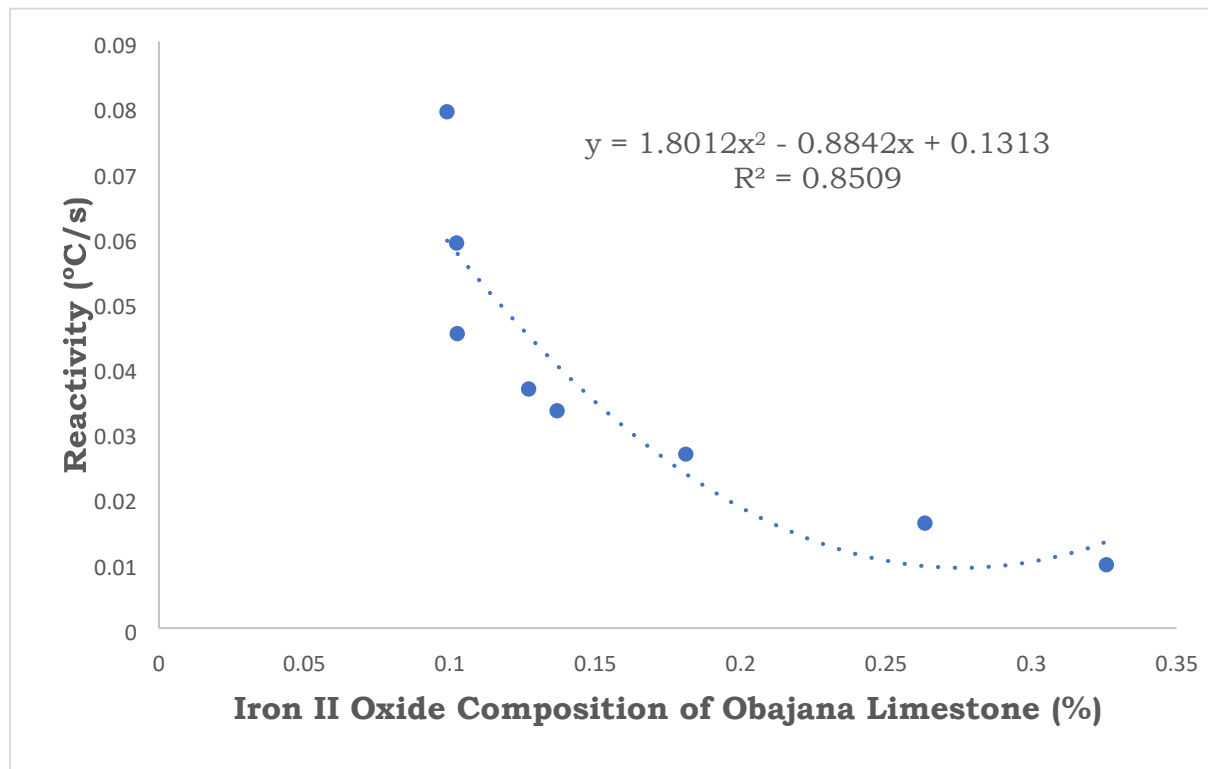


Figure 7. Exponential Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

Figures 8–12: Empirical Models for 0.45 mm Limestone Particle Size

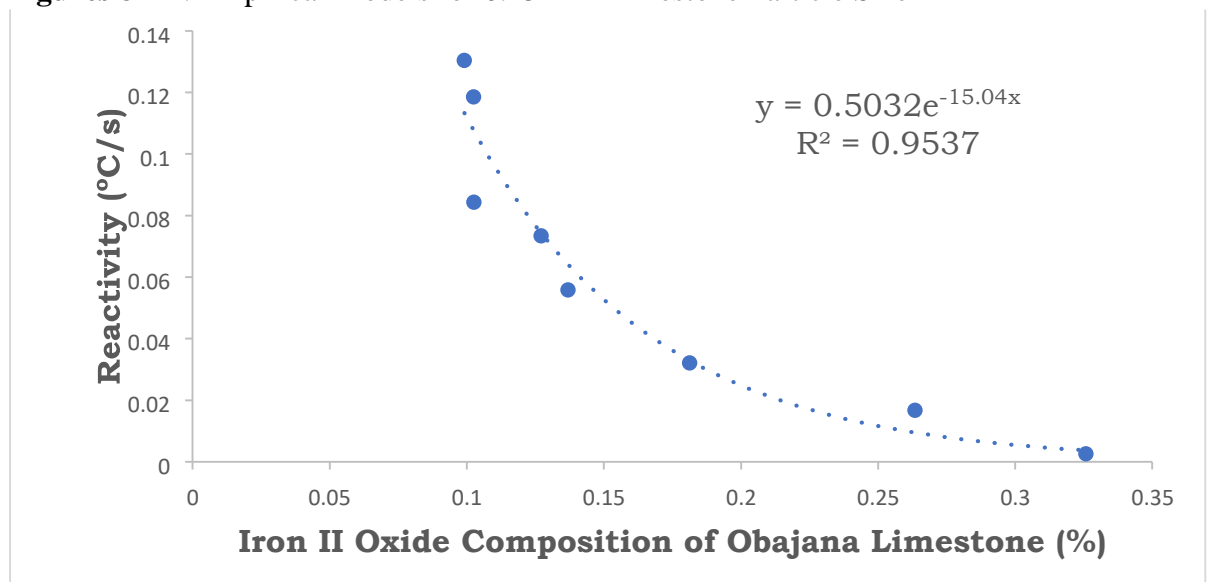


Figure 8. Exponential Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

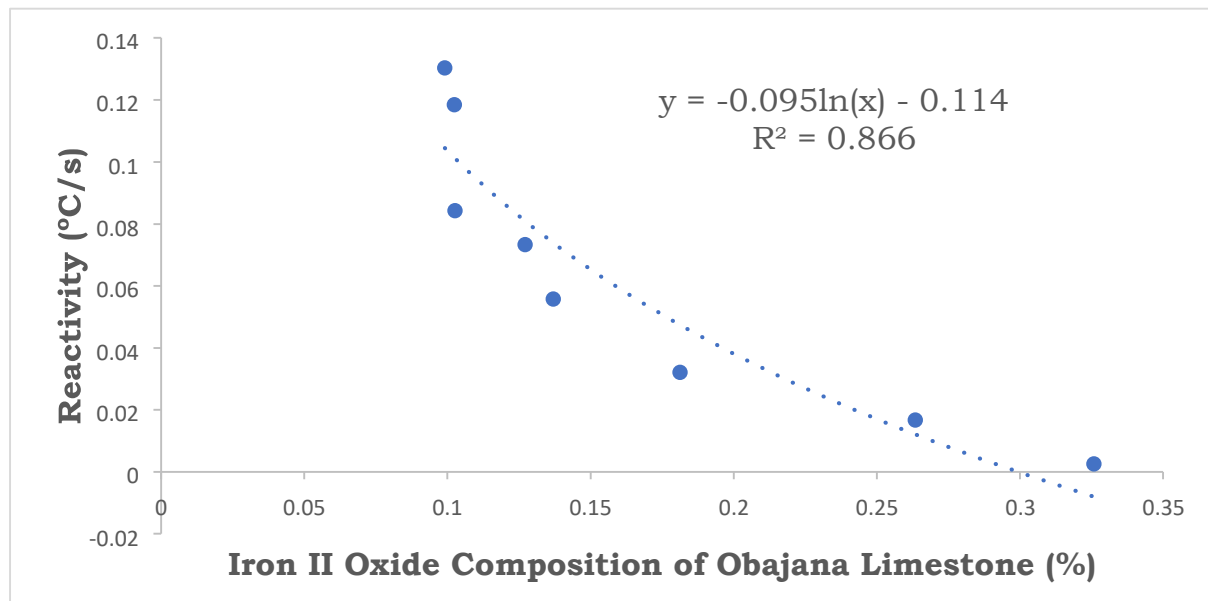


Figure 9. Logarithmic Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

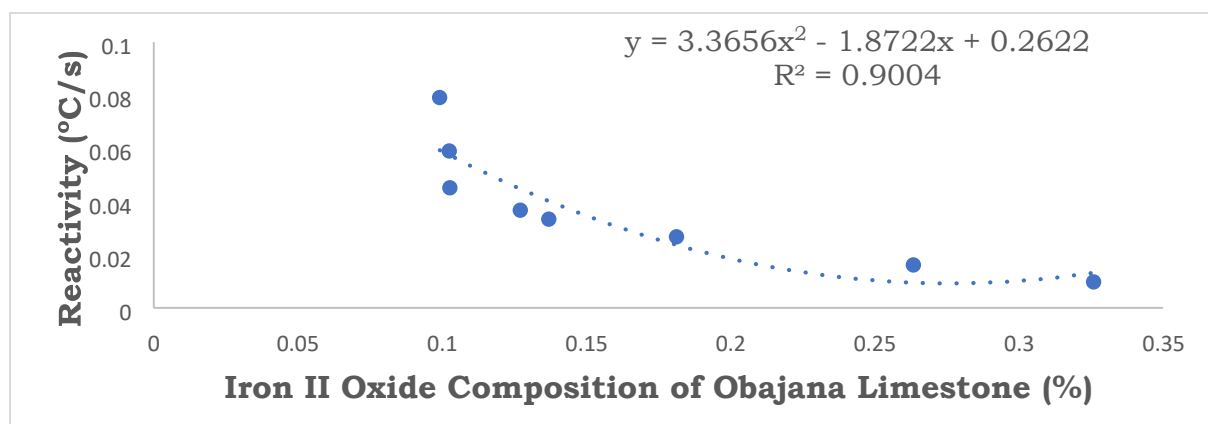
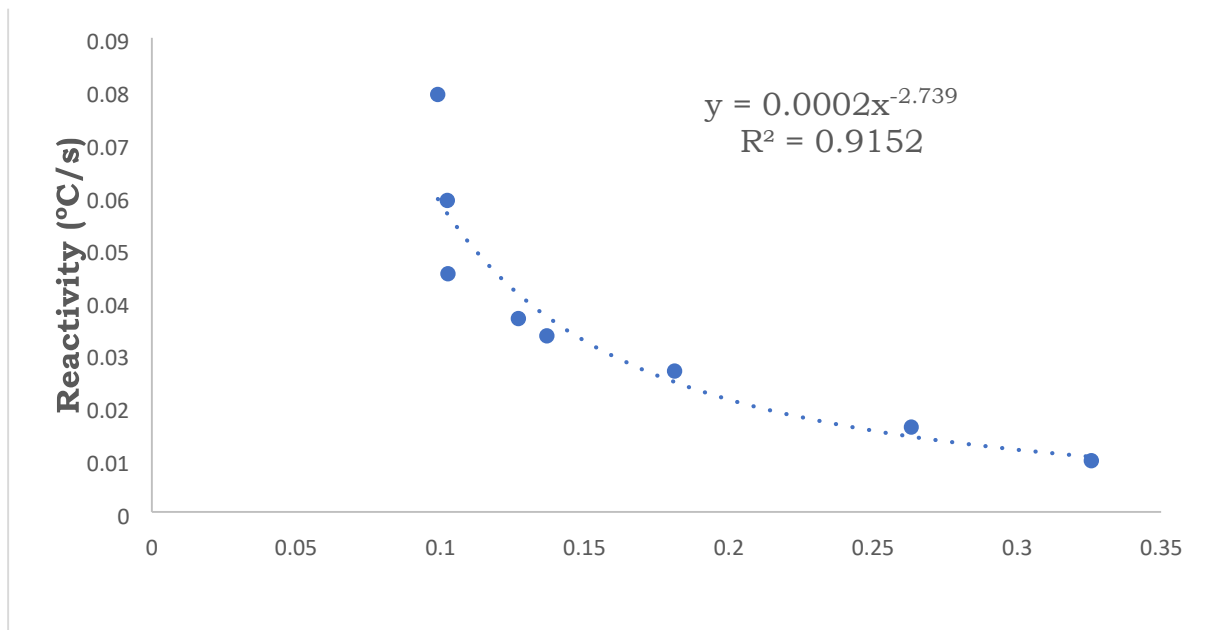


Figure 10. Polynomial Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm



Iron II Oxide Composition of Obajana Limestone (%)

Figure 11. Power Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm.

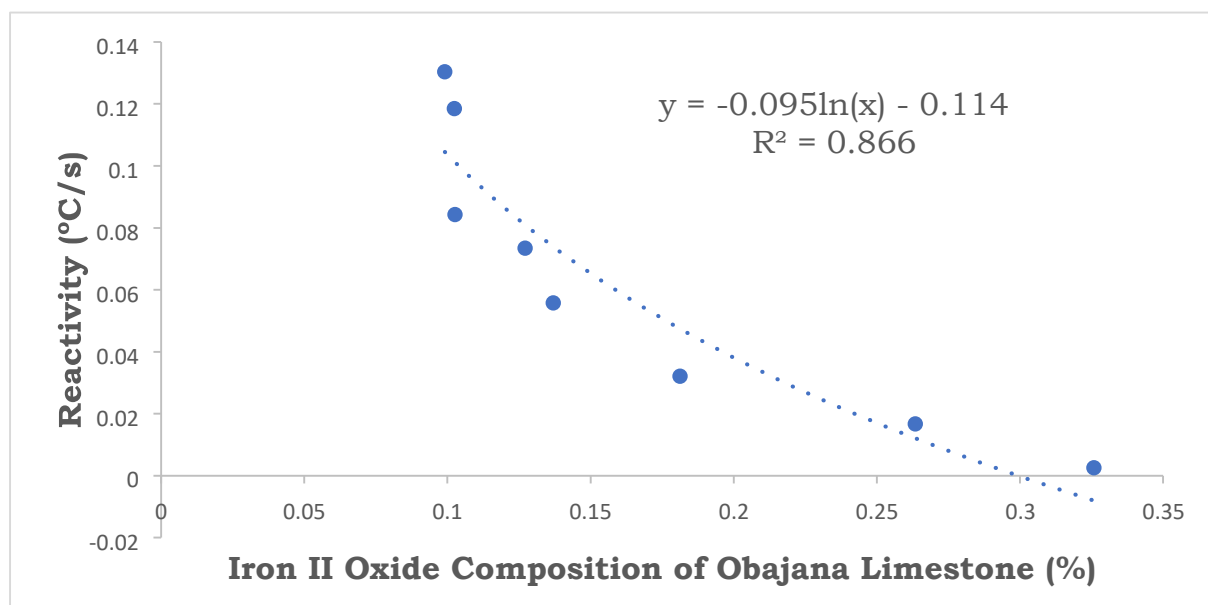


Figure 12. Linear Model of Obajana Limestone Showing the Variation of its Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

Table 5. Statistical Precision Analysis for Comparing the Experimental to the Simulated Results for Quicklime Reactivity against Composition for Particle Size of 0.25 mm

Statistical Parameters	Value
Correlation Coefficient	0.7029
Adjusted Correlation Coefficient	0.494
Covariance	0.00359
Standard Error	0.019

Standard Deviation	0.189
Variance	0.036

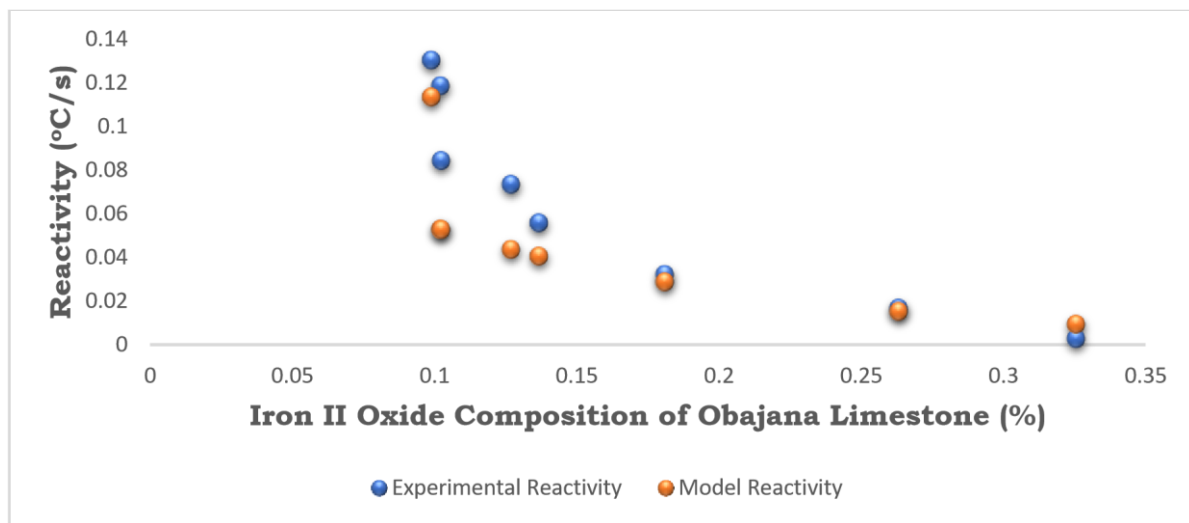


Figure 13. Exponential Model of Obajana Limestone Showing the Variation of its Experimental and Model Quicklime Reactivity against Iron II Oxide Composition for Particle Size of 0.25 mm

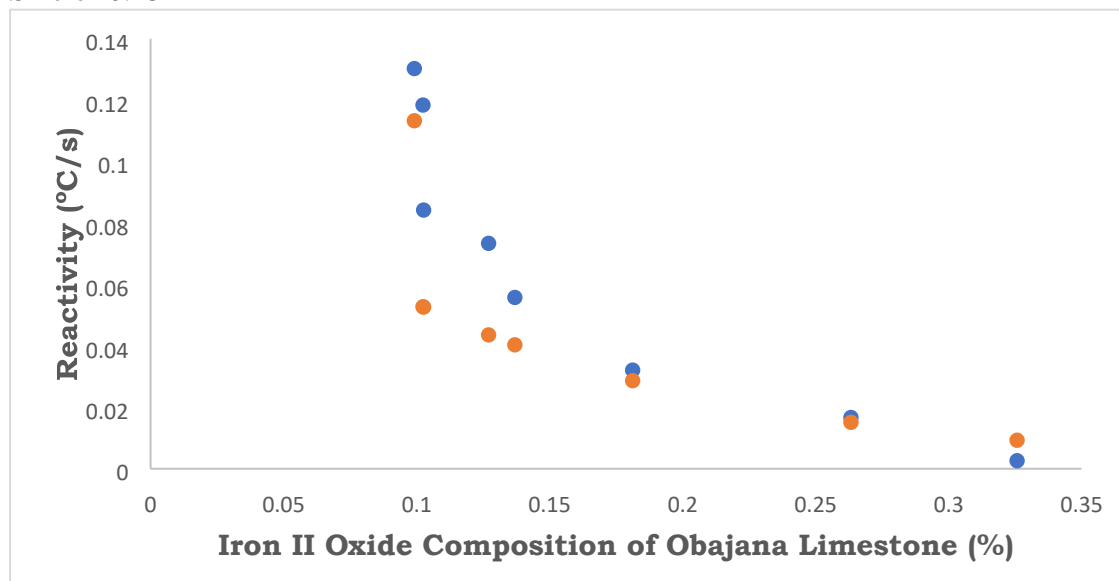


Figure 14: Exponential Model of Obajana Limestone Showing the Variation of its Experimental and Model Quicklime Reactivity against Iron II Oxide Composition for Particle Size of 0.45 mm

4.4. Comparison with Previous Studies and Implications for Sustainable Lime Production

The inverse relationship between Iron II Oxide content and quicklime reactivity observed in this study is consistent with earlier findings, which report that metallic impurities adversely affect the calcination process and the resultant reactivity of quicklime (Akande, 2015; Moropoulou et al., 2001). The decrease in reactivity with increasing Iron II Oxide suggests that controlling impurity levels is critical for optimizing calcination and slaking processes. Integrating the validated exponential model into renewable energy-driven calcination systems could enable more precise control over process parameters, thereby enhancing energy

efficiency and reducing carbon emissions. This approach is particularly relevant for sustainable industrial decarbonization strategies, as it facilitates the production of high-quality quicklime with lower energy consumption.

4.5. Challenges, Limitations, and Future Research Directions

While the developed exponential model demonstrates robust predictive capability within the defined experimental domain, several challenges and limitations should be noted. The current model is based on a specific range of particle sizes (0.25 mm and 0.45 mm) and Iron II Oxide compositions. Variability in other process parameters—such as slaking water type, water temperature, and stirring speed—was not addressed and could influence reactivity outcomes. Future research should incorporate advanced characterization techniques (e.g., X-ray diffraction, scanning electron microscopy) to develop more comprehensive models. Additionally, exploring the effects of different renewable energy sources on the calcination process could further optimize sustainable calcination processes.

5. CONCLUSION

This study has demonstrated the significant impact of Iron II Oxide (FeO) composition on the reactivity of quicklime produced from Obajana limestone. Key findings indicate that higher FeO levels decrease quicklime reactivity, with reactivity declining from 0.0792 °C/s to 0.0097 °C/s for 0.25-mm particles and from 0.1304 °C/s to 0.0026 °C/s for 0.45-mm particles as FeO content increased from 0.0991% to 0.3258%. The developed empirical models, particularly the exponential model, provided robust predictive capabilities with R² values of 92.15% and 95.37% for 0.25-mm and 0.45-mm particles, respectively. These results underscore the importance of controlling impurity levels in sustainable lime production. The study contributes to the field of sustainable industrial decarbonization by providing a pathway to optimize lime calcination processes using renewable energy sources, thereby enhancing energy efficiency and reducing carbon emissions. Future research should explore advanced characterization techniques and the effects of different renewable energy sources on the calcination process to further optimize sustainable lime production.

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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.

7. REFERENCES

Akande, H. F. (2015). *Multiple response surface optimization of quicklime production from limestone using design of experiment* [Doctoral dissertation, Federal University of Technology, Minna]. Available on Google Scholar.

- Moropoulou, A., Bakolas, A., & Aggelakopoulou, E. (2001). The effect of limestone characteristics and calcination temperature on the reactivity of quicklime. *Cement and Concrete Research*, 31(7), 633–639. Available on ResearchGate.
- Doddapaneni, P., Tatineni, R., Potumarthi, R., & Mangamoori, L. (2007). Optimization of keratinase production and enzyme activity using response surface methodology with streptomyces sp7. *Applied Biochemistry and Biotechnology - Part A Enzyme Engineering and Biotechnology*, 141(2-3), 187-201. Available on Monash University Research Portal.
- Montgomery, D. C., Peck, E. A., & Vining, G. G. (2009). *Introduction to linear regression analysis* (5th ed.). Wiley. Available on O'Reilly Media.
- Oates, J. A. H. (1998). *Lime and limestone: Chemistry and technology, production and uses*. Wiley-VCH. Available on Google Books

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