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ARTICLE

Flash Calcination of Kaolinite Clay in a Pilot Reactor: Evaluation of Clay Color Change in Oxidizing, Inert and Reducing Atmospheres

Gabriel Henrique Wienhage [1], ***Vinícius Henrique de Freitas*** [2], ***Julio Zeppone Carlos*** [2], ***Luis Filipe von Rainer Fabiani*** [2], ***Luiz Felipe de Pinho*** [2], ***Rodrigo de Souza Borges*** [2], ***Vinicyus Rodolfo Wiggers*** [1*]

[1] *University of Blumenau, Chemical Engineering Post-Graduation Program, São Paulo Street, 3250, Blumenau, SC 89030-000, Brazil*

[2] *Dynamis Engineering and Commerce, São Paulo, SP 05024-030, Brazil*

ABSTRACT

Cement production, while essential for global infrastructure, contributes significantly to carbon dioxide emissions, accounting for approximately 7% of total emissions. To mitigate these environmental impacts, flash calcination of kaolinitic clays has been investigated as a sustainable alternative. This technique involves the rapid heating of clays, enabling their use as supplementary cementitious materials. The primary objective of this study was to modify the color of calcined clay in various atmospheres (oxidizing, inert, and reducing) to achieve a grayish tone similar to commercial cement while preserving its reactive properties. The experimental procedure employed a tubular reactor with precise control of gas flows (atmospheric air, nitrogen, and a carbon monoxide–nitrogen mixture). Physicochemical characterization of the raw clay was conducted before calcination, with analyses repeated on the calcined clays following experimentation. Results indicated that clay calcined in an oxidizing atmosphere acquired a reddish hue, attributed to the oxidation of iron in hematite. The Clay exhibited a pinkish tone in an inert atmosphere, while calcination in a reducing atmosphere yielded the desired grayish color. Regarding pozzolanic activity, clays calcined in oxidizing and inert atmospheres displayed robust strength, ranging from 82% to 87%. Calcination in a reducing atmosphere resulted in slightly lower strength, around 74%, likely due to the clay's chemical composition and the calcination process, which affects compound formation and material reactivity.

*CORRESPONDING AUTHOR:

Vinicyus Rodolfo Wiggers, University of Blumenau, Chemical Engineering Post-Graduation Program, São Paulo Street, 3250, Blumenau, SC 89030-000, Brazil; Email: vwiggers@furb.br

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1. Introduction

Cement is among the most widely consumed materials globally. According to the Global Cement and Concrete Association (GCCA), approximately 150 tons of cement are used every second, equating to 14 billion cubic meters of concrete annually. Cement production accounts for approximately 7% of global CO_2 emissions, representing a substantial environmental impact[1–3]. In Brazil, this figure is reduced to approximately 2.6%, primarily due to the lower clinker content in cement, achieved by incorporating supplementary cementitious materials (SCMs)[4].

Approximately 80% of the materials used to reduce clinker content in cement production are derived from fly ash and blast furnace slag. However, it is crucial to note that access to these resources varies by country, as they are byproducts of specific industrial processes[5]. In terms of domestic production, around 7.38 million tons of slag were generated in 2014, primarily from pig iron production. Regarding fly ash, about 30% of global cement production incorporates this material. Nonetheless, the quality of available fly ash to limit its broader application, with only around 30% of total production meeting the standards required for cement manufacturing[6, 7].

Brazil has an emission factor of approximately 610 kg CO_2 per ton of cement, compared to 698 kg CO_2/ton in Spain, 839 kg CO_2/ton in the United Kingdom, and 848 kg CO_2/ton in China. Considering these figures, the cement industry is increasingly exploring the replacement of calcined limestone with calcined clay, a widely available supplementary cementitious material (SCM). Kaolinitic clay, represented chemically as $Al_2Si_2O_5(OH)_4$, may contain trace amounts of iron oxides, quartz, and calcium oxide, among other minerals. When calcined, kaolin is transformed into metakaolin, an SCM that is a viable substitute for calcined limestone[8, 9].

The use of metakaolin offers the potential to partially offset the clinker required in cement production. Moreover, studies indicate that incorporating metakaolin can enhance cement performance by increasing compressive strength, reducing permeability, and improving durability, positioning it as an appealing alternative for the cement industry[10, 11].

Some works and patents were developed based on studies of flash calcination and/or color modification of calcined kaolinitic clay: [12–18], among others.

The dehydroxylation of these materials occurs due to the interaction of two independent processes during calcination. Recent studies on flash calcination have demonstrated that the rapid temperature gradient applied to finely ground, kaolinite-rich clay within a few seconds enables swift dehydroxylation. This approach offers a faster, more thermally efficient mechanism for producing supplementary cementitious materials. Notably, the most significant research on SCM production through flash calcination has primarily focused on kaolinitic clays[19–23].

Initially, the process involves the loss of interlayer water from the clay (dehydration), occurring at temperatures above 100 °C, as illustrated in Equation (1). Subsequently, the material undergoes a discontinuous loss of structural water (dehydroxylation). During dehydroxylation, the hydroxyl groups within the kaolinite structure are progressively eliminated as the temperature rises. This dehydroxylation is a critical step in converting kaolinite into metakaolinite[18, 24, 25].

As indicated in Equation (2), this reaction occurs within a temperature range of 450 to 700 °C. This range is crucial for the proper formation of metakaolin; too low temperatures will not facilitate the necessary reactions, while excessively high temperatures may lead to the improper synthesis of metakaolin[26, 27].

It is important to note that metakaolin is not a thermodynamically stable phase and may begin to transform into mullite and other crystalline phases at temperatures exceeding 925 °C, as shown in Equation (3). Therefore, precise temperature control during synthesis is essential to prevent the undesired formation of secondary phases. Such transformations should be avoided, as they can adversely impact the material final material's properties. The relevant reaction equations are presented below[3].

$$H_2O_{(l)} \xrightarrow{100\,°C\ (373,15\ K)} H_2O_{(g)} \tag{1}$$

$$Al_2Si_2O_5(OH)_4 \xrightarrow{450\ -\ 700\,°C\ (723,15\ -\ 973,15\ K)} Al_2Si_2O_7+2H_2O_{(g)} \tag{2}$$

$$3\,(Al_2Si_2O_7) \xrightarrow{925\,°C\ (1198,15\ K)} Al_6Si_2O_{13}+4SiO_2 \tag{3}$$

It is crucial to emphasize that the amorphous phase resulting from the transformation of metakaolin at temperatures above 925 °C continues to convert into silicon dioxide at even higher temperatures. This undesirable transformation leads to increased crystallinity, thermal instability, and reduced reactivity of the final material.

One of the challenges the cement industry encounters is the reddish color of calcined clay, which arises from the presence of hematite (Fe_2O_3), a prevalent mineral in the Earth's crust and commonly found in clays. The reddish color of calcined kaolinitic clay impacts the commercial appeal of cement, as this hue is not favored within the construction industry. Calcination in a reducing atmosphere, such as carbon monoxide (CO), has been proposed. Reducing Fe_2O_3 to metallic iron (Fe) using CO is a heterogeneous process involving multiple elementary reactions. The reduction process is characterized by evaluating the reaction rates of the involved reactions, as described in Equations (4)–(7)[28, 29].

$$Fe_2O_3 + 1/3\,CO_{(g)} \quad \rightarrow \quad 2/3\,Fe_2O_4 + \ 1/3\,CO_{2(g)} \tag{4}$$

$$Fe_2O_4 + \ CO_{(g)} \quad \rightarrow \quad 3\,FeO + \ CO_{2(g)} \tag{5}$$

$$FeO + \ CO_{(g)} \quad \rightarrow \quad Fe + \ CO_{2(g)} \tag{6}$$

$$Fe_3O_4 + \ 4\,CO_{(g)} \quad \rightarrow \quad 3\,Fe + 4\,CO_{2(g)} \tag{7}$$

The reduction of hematite results in a more grayish tone of clay, enhancing its attractiveness for the commercial cement market. The primary objective of this study is to conduct flash calcination of clay under various atmospheres (atmospheric air, nitrogen, and carbon monoxide) and to assess the color change of the calcined material alongside its physicochemical properties.

2. Methods and Material

2.1. Material

The clay used in this study was sourced from Brasília (DF) by Ciplan Cimentos and supplied by Dynamis Engenharia e Comércio LTDA for research purposes. The sample was sent to the Process Development Laboratory at the University of Blumenau for analysis following collection. To identify the mineral phases, present in the clay, X-ray diffraction (XRD) was employed, as reported by Ciplan Cimentos, the company responsible for sample collection. This technique enables the identification of the crystalline phases within the clay. The chemical composition of the clay is presented in **Table 1**.

The clay under investigation primarily consists of SiO_2 and Al_2O_3, with a loss on ignition of 10%. For flash calcination in different atmospheres, oxidizing, inert, and reducing. Three gases were selected: atmospheric air, nitrogen, and a carbon monoxide-nitrogen mixture.

The clay contains hematite (Fe_2O_3) as part of its chemical composition. During the flash calcination process, the reduction of Fe_2O_3 occurs, directly influencing the clay's coloration. Consequently, carbon monoxide is a reducing agent to achieve the desired effect.

In this research, Portland cement CP II—F32 was used. This cement type contains a limestone filler and is characterized by achieving a compressive strength of 32 MPa after 28 days of curing, in accordance with EN 197-1:2000 standards. The selection of this cement type was based on the absence of pozzolanic additives, thereby minimizing potential interferences in analyzing the effects of the calcined clays investigated in this study.

Four sand fractions were utilized for the pozzolanic activity tests, with particle sizes of 1.18 mm, 600 µm, 300 µm, and 150 µm. Each sand fraction underwent a washing procedure, followed by drying in an oven at a controlled temperature of 100 ± 10 °C for 24 hours.

2.2. Methods

The study involved a detailed sample preparation process for the flash calcination experiments in various atmospheres. Initially, the clay was dried at 100 °C for 24 hours. The dried clay was then subjected to ball milling with a clay-to-ball ratio of 1:5 for 4 hours to ensure homogenization. Following the milling process, a particle size analysis was performed, and a fire loss analysis was conducted at 950 °C for 50 minutes.

Following the preparation of the clay, nine flash calcination experiments were planned. For each set of experiments, 2 kg of dried virgin clay was introduced into the feed reservoir. The furnace setpoint temperature was maintained at 970 °C, with a gas flow rate of 70 L/min. Initially, experiments were conducted using 100% atmospheric air, designated as experiments 1, 2, and 3. Subsequently, experiments were performed in a fully inert atmosphere (nitrogen), labeled as

Table 1. Chemical composition of virgin clay.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	K_2O	LOI*
55.7	24.3	5.4	0.1	0.2	1.8	0.1	10.7

*LOI - Loss on ignition
Source: Dynamis Engenharia e Comércio LTDA and Ciplan Cimentos (2022).

experiments 4, 5, and 6. Finally, to examine flash calcination in a reducing atmosphere (experiments 7, 8, and 9), a gas mixture containing 2.5% carbon monoxide and 97.5% nitrogen was employed. Preliminary runs varying the CO concentration from 1% to 10% indicated that a concentration of 2.5% CO changes the material's color.

The flash calcination experiments of the clay were conducted in a pilot-scale vertical tubular reactor. The experimental setup includes a 30 kW preheating furnace at the reactor's base, equipped with a stainless-steel coil connected to the gas feed system. On the side of the reactor, there is a material reservoir and a rotary screw feeder for continuous material feeding into the reactor. The reactor is 2 meters tall, with an internal diameter of 62 mm, and is equipped with 14 thermocouples (T_{01}, T_{02}, …, T_{14}) distributed along its length for precise temperature monitoring. At the top, the reactor is equipped with two cyclones in series and two reservoirs for collecting the calcined material, followed by a bag filter to capture any remaining solids in the gas stream. During the experiments in the pilot plant, a solid-to-hot gas ratio of 1 kg of solid per 5 kg of hot gas was used. However, the solid-to-hot gas ratio may be reduced on an industrial scale depending on the process design. **Figure 1** illustrates the reactor's schematic.

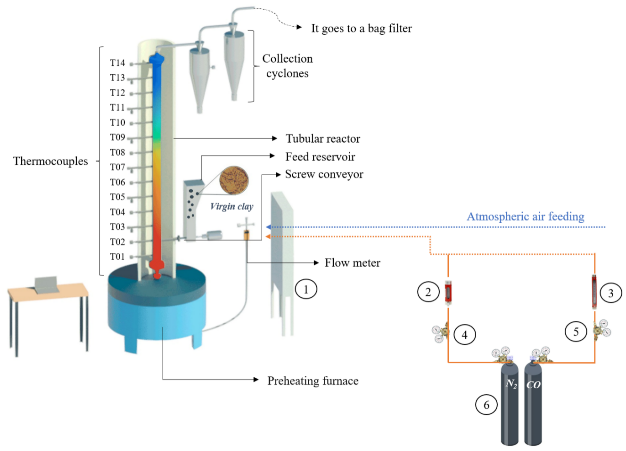

Figure 1. Schematic of pilot-scale flash calcination reactor.

Note: (1) Reactor control panel; (2) nitrogen current rotameter; (3) carbon monoxide current rotameter; (4) nitrogen flow control valve; (5) carbon monoxide current control valve and (6) nitrogen and carbon monoxide cylinders.

The loss on ignition of calcined clays was carried out based on Standard NM 18 ABNT, 2012b. To evaluate the pozzolanic activity index relative to Portland cement, reference mortars (I) and mortars with a 25% replacement of cement by the pozzolanic material under investigation (II) were prepared, following the methodology described by[1]. Three samples of calcined clays, corresponding to experiments 1, 4, and 7, were selected for this assessment. To ensure the reliability of the results, each analysis was conducted in duplicate, utilizing six test specimens per experiment. In total, 48 test specimens were employed in this study.

For the preparation of mortar I, 624 g of Portland cement CP-II-F32, 1872 g of sand, 300 g of water, and approximately 2 g of superplasticizer were used. For the preparation of mortar II, 468 g of Portland cement CP-II-F32, 156 g of calcined clay, 468 g of sand, 300 g of water, and around 2 g of superplasticizer were used.

For colorimetric analysis aimed at identifying color variations between raw clay and calcined clay samples under different atmospheres, a Lovibond SP60 spectrophotometer was used. The analysis relies on the L, a, and b parameters, a coordinate system essential for describing and quantifying color properties. The L parameter (Luminosity) measures color intensity, ranging from 0 (black) to 100 (white), with higher values indicating greater brightness. A parameter represents color variation along the red-green axis, with positive values indicating reddish tones and negative values indicating greenish tones. The b parameter reflects variation along the yellow-blue axis, with positive values indicating yellowish tones and negative values indicating bluish tones[30].

To analyze the morphology of clay particles, a SEM was used, providing detailed visualization of the sample structures and allowing observation of characteristics such as shape and size. The morphology was examined for both raw clays and samples 2, 5, and 8, with magnifications of 1000x, 2500x, 5000x, 10000x, and 15000x. Particle distribution was performed in a Malvern Mastersizer 2000 using the laser diffraction technique.

3. Results and Discussion

After preparing the raw clay, the flash calcination experiments in different atmospheres were initiated. **Table 2** provides a summary of these experiments, including the average reactor temperature ($\bar{T}_R$), gas flow rate, particle residence time (t_R), and the Loss on ignition (LOI) analysis after calcination.

To determine the t_R, the $\bar{T}_R$ was first calculated according to Equation (8), and the average specific mass $(\bar{\rho})$, as described in Equation (9). Finally, t_R was determined using the reactor height (h_R), in accordance with Equation (10).

$$\bar{T}_R = \sum_{i=2}^{n=14} T \Big/ n \tag{8}$$

$$\bar{\rho} = \frac{P \cdot \bar{MM}}{R \cdot \bar{T}_R} \tag{9}$$

$$t_R = \frac{h_R}{\bar{v}} \tag{10}$$

Where P is the pressure (atm), R is the universal gas constant (0.082 atm·L/mol·K) and $\bar{v}$ is the gas velocity in the reactor (m/s).

Table 2. Experimental data on the calcination of kaolinite clay in oxidizing, inert, and reducing atmospheres.

Experiment		$\bar{T}_R$ °C	Gas Flow l/min	tR s	LOI %
Oxidant	1	$501^{\pm 9.1}$	$80^{\pm 10.3}$	1.7	3.0
	2	$490^{\pm 4.5}$	$77^{\pm 9.0}$	1.8	2.8
	3	$473^{\pm 6.5}$	$71^{\pm 9.0}$	2.0	3.0
Average	-	$488^{\pm 6.7}$	$76^{\pm 9.4}$	$1.8^{\pm 0.15}$	$2.9^{\pm 0.11}$
Inert	4	$454^{\pm 4.8}$	$70^{\pm 0.2}$	2.0	2.5
	5	$473^{\pm 4.1}$	$70^{\pm 3.8}$	2.0	2.4
	6	$475^{\pm 6.2}$	$70^{\pm 0.2}$	2.0	2.4
Average	-	$467^{\pm 5.1}$	$70^{\pm 1.4}$	$2.0^{\pm 0.0}$	$2.4^{\pm 0.02}$
Reducer	7	$443^{\pm 3.7}$	$70^{\pm 1.0}$	2.1	2.36
	8	$464^{\pm 3.9}$	$69^{\pm 0.2}$	2.0	2.35
	9	$452^{\pm 14.6}$	$55^{\pm 11.7}$	2.6	2.19
Average	-	$453^{\pm 10.4}$	$65^{\pm 8.0}$	$2.2^{\pm 0.30}$	$2.3^{\pm 0.09}$

After analyzing the experiments conducted in an oxidizing atmosphere (1, 2, and 3), the average reactor temperature showed slight variation between tests, with an average of 488 °C. There was a variation in the gas flow rate due to the compressor's limitation in maintaining a constant flow of 70 l/min, leading to an increase in the residence time of the clay particles in the reactor. This evidences a relationship between the gas flow rate and the residence time of the particles in the reactor. The loss on ignition analysis showed consistent values, with an average of 2.9%. The consistency of these results indicates that calcined clay meets the standards to be considered a pozzolan.

The analysis of data obtained from three calcination experiments of kaolinitic clay in an inert atmosphere (experiments 4, 5, and 6) using nitrogen showed that the inert gas flow rate was maintained at 70 L/min, indicating effective process control. The material's residence time was around 2 seconds. Notably, the loss on ignition remained constant at 2.4%, suggesting consistency in the clay composition or process efficiency. These results indicate reproducibility and stability in the calcination process.

The analysis of the kaolinitic clay calcination experiments in a reducing atmosphere (experiments 7, 8, and 9) revealed variations in operational parameters. The gas flow rate ranged from 55 to 70 L/min due to the reduction in the carbon monoxide cylinder's internal pressure. The residence time varied from 2 to 2.6 seconds, directly influenced by the low pressure of the gas cylinder. These results highlight the significant influence of the reducing atmosphere on the clay calcination process.

The bulk density values ranged from 2.45 to 2.50 g/cm³, indicating a nearly insignificant variation compared to the raw sample, which had a bulk density of 2.49 g/cm³.

3.1. Colorimetric Analysis of Clays Calcined in Oxidizing, Inert, and Reducing Atmospheres

After completing the calcination experiments, the samples were subjected to colorimetric analysis. The obtained L, a, and b parameters are shown in **Table 3**.

Initially, a significant change in coloration is observed, which can be attributed to the oxidation of iron present in the clay's structure. The Fe_2O_3 content of the raw clay is 5.4%. According to [31], kaolinitic clays with a low Fe_2O_3content, around 2% to 9%, when calcined in an oxidizing atmosphere at temperatures between 350 and 600 °C, show an intensification of the reddish color. This intensification is due to the formation of hematite, although at around 650 °C, a magnetite transformation occurs because of oxygen during the clay's cooling process. Analyzing the colorimetric coordinates, it is observed that the L parameter (luminosity) did not show a significant change. However, the a parameter increased from 3.64 to a range of 6.60 to 7.50, indicating an intensification of the reddish color in the clay calcined in an oxidizing atmosphere. The b parameter also showed a significant increase, indicating an intensification of the yellowish color in the sample.

Table 3. Evaluation of the colorimetric change of calcined clay in different atmospheres using a Lovibond SP60 spectrophotometer.

Experiment		Parameters			Colors
		L*	a*	b*	
Virgin clay		64.0	5.2	16.0	🟫
Portland Cement CP-II-F32		37.2	1.2	6.6	⬛
Oxidant	1	71.8	7.5	20.5	🟫
	2	61.2	3.2	12.4	🟫
	3	67.9	5.6	15.4	🟫
Average	-	$66.9^{\pm 5.4}$	$5.4^{\pm 2.2}$	$16.1^{\pm 4.1}$	🟫
Inert	1	63.4	5.6	19.6	🟫
	2	70.6	1.7	8.1	🟫
	3	54.0	4.0	13.6	🟫
Average	-	$62.7^{\pm 8.3}$	$3.8^{\pm 1.9}$	$13.8^{\pm 5.8}$	🟫
Reducer	1	65.8	0.3	7.8	⬛
	2	56.1	−0.004	4.8	⬛
	3	62.5	−0.4	3.4	⬛
Average	-	$61.4^{\pm 5.0}$	$0.1^{\pm 0.5}$	$5.4^{\pm 2.2}$	⬛

L* - luminosity
a* - red/green coordinate
b* - yellow/blue coordinate

When clay is subjected to an inert atmosphere, without oxygen, it does not transform into magnetite when calcined at any temperature range. As a result, its color does not intensify to a reddish hue, becoming more grayish instead [31]. Analyzing the colorimetric coordinates of the calcination in an inert atmosphere, it is observed that the L parameter showed a slight increase in luminosity, meaning the colors became slightly darker. The a and b parameters increased compared to the clay in its raw state; thus, being on the positive axis, its coloration intensified more towards reddish and yellowish tones.

When kaolinitic clay is calcined in a reducing atmosphere, the conversion of magnetite to hematite is inhibited, resulting in a grayish color, similar to that of commercial cement. This calcined clay is commonly used as a building material[32]. In experiments conducted in a reducing atmosphere, the luminosity parameter increased, indicating that the material intensified its color. A parameter varied from -0.004 to 0.6, with the negative value suggesting that the clay's color shifted towards a more greenish hue. In contrast, the b parameter, with an average of 5.4, indicated a more yellowish tone.

3.2. SEM Analysis of Clay Samples

Figure 2 shows the raw virgin clay sample, which serves as a reference point for comparing with the other samples. Initially, the raw clay's d(0.9) particle size was 40 µm.

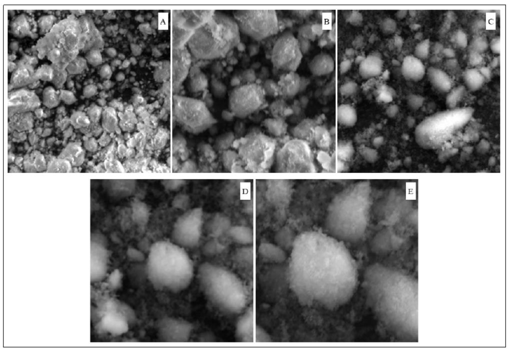

Figure 2. SEM analysis of the raw clay with a d(0.9) particle size of 40 µm at magnifications of 1000x (**A**), 2500x (**B**), 5000x (**C**), 10000x (**D**), and 15000x (**E**).

Microstructural analyses of the raw clay reveal various geometric arrangements of particles, which vary in size due to the high degree of fineness. A range of shapes is observed, with particles having rounded edges and a significant prevalence of irregular forms. The particles exhibit an opaque structure and low reactivity, indicating minimal interaction between the samples. This is particularly noticeable in the samples that were not subjected to thermal treatments, suggesting that the original properties of the clay have been preserved.

A SEM analysis, shown in **Figure 3**, was conducted to assess potential morphological changes and dehydroxylation of calcined clay particles in an oxidizing atmosphere.

After the raw clay underwent calcination in an oxidizing atmosphere, it was observed that the particles tended to agglomerate, resulting in a more compact structure and a significant increase in surface area. Initially 40 µm, the particle size increased by approximately 64% after calcination, reaching around 109 µm. This increase is attributed to the tendency of particles to unite and form clusters during the process. This phenomenon was also observed in the study by[1] where calcined samples showed a substantial amount of agglomerated material, reflecting the removal of hydroxyl groups and the structural rearrangement typical of calcination.

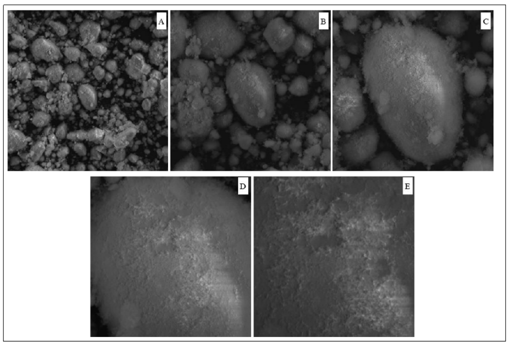

Figure 3. SEM analysis of clay calcined in an oxidizing atmosphere, with an approximate d(0.9) particle size of 109.12 µm at magnifications of 1000x (**A**), 2500x (**B**), 5000x (**C**), 10000x (**D**), and 15000x (**E**).

Compared to calcination in an oxidizing atmosphere, the d(0.9) particle size of the clay exhibited the same phenomenon described earlier, increasing from 40 to 94 µm, as shown in **Figure 4**.

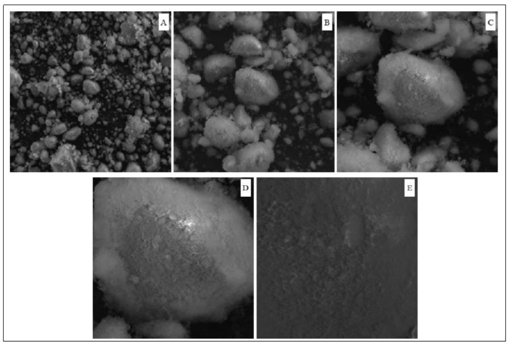

Figure 4. SEM analysis of clay calcined in an inert atmosphere, with an approximate d(0.9) particle size of 94.25 µm at magnifications of 1000x (**A**), 2500x (**B**), 5000x (**C**), 10000x (**D**), and 15000x (**E**).

Figure 5 shows the SEM analysis of the clay sample calcined in a reducing atmosphere.

Comparing the SEM analysis with previous results, no significant changes in particle structure were observed. However, a particle agglomeration was noted in the all samples calcined.

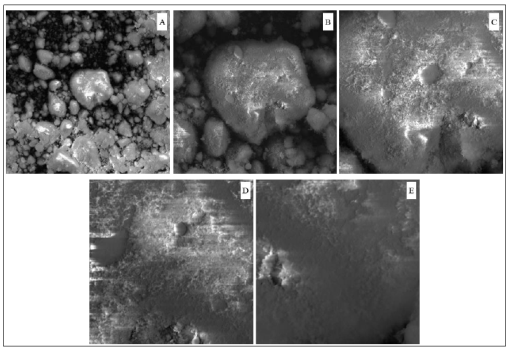

Figure 5. SEM analysis of clay calcined in a reducing atmosphere, with an approximate d(0.9) particle size of 84.89 µm, at magnifications of 1000x (**A**), 2500x (**B**), 5000x (**C**), 10000x (**D**), and 15000x (**E**).

The tests for pozzolanic activity were identified as R.I and R.II (references 1 and 2), Exp. 1 and 2 for clays calcined in an oxidizing atmosphere, Exp. 3 and 4 for clays calcined in an inert atmosphere, and Exp. 5 and 6 for clays calcined in a reducing atmosphere. The results of the breakage tests are presented in **Figure 6**. The values ranged from 74% to 87% of the reference. These parameter specifications vary according to different regulations.

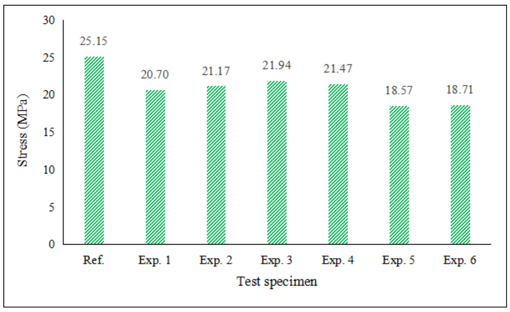

Figure 6. Data on the pozzolanic activity index of the test specimens for clays calcined in different atmospheres, with breakage after 28 days of curing.

4. Conclusions

The cement industry faces a challenge in the commercialization of cement whose calcined clays exhibit a reddish coloration. Therefore, the primary objective of this study was to investigate the color change of the studied clay under different atmospheres: oxidizing, inert, and reducing. It was observed that the clay in its natural state is reddish due to the presence of hematite and other metals. When the clay is subjected to calcination in atmospheric air using combustion gases, this reddish color intensifies because of iron oxidation. In contrast, when calcination occurs in an inert atmosphere, the color becomes more grayish or pinkish. In a reducing atmosphere, the clay's color turns more grayish, like cement's.

It was found that the change in atmosphere significantly affects the color of the clay, as demonstrated by variations in the colorimetric coordinates L, a, and b, where a+ parameter indicates the intensification of the reddish color, and the b+ parameter indicates the intensification of the yellowish color.

Another aspect analyzed was the strength of the calcined clay. The experiments conducted with calcination in atmospheric air and nitrogen ranged from 82% to 87%. These results suggest that these materials can be used as additives in cement, according to standard specifications. Unaddressed topics such as cooling, agglomeration, water absorption, structural changes, and long-term durability tests, require extensive research[32–34]. Furthermore, this study highlights that flash calcination in reduction atmospheres can alter the color of calcined clay, which is highly relevant to the cement industry's efforts to reduce CO_2 emissions.

Author Contributions

G.H.W.: Writing – review and editing, methodology, investigation. V.R.W.: Writing – review and editing, methodology, conceptualization, supervision. V.H.d.F.: Methodology, investigation and review. J.Z.C.: Methodology, conceptualization and review. L.F.v.R.F.: Supervision and review. L.F.d.P.: Conceptualization, methodology and review. R.d.S.B.: Methodology and review. All authors have read and agreed to the published version of the manuscript.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

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