
STUDY OF THE CHEMICAL COMPOSITION OF CEMENT RAW MATERIALS FOR CLINKER FORMATION IN CEMENT PRODUCTION

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Abstract

Cement production relies on the careful selection and proportioning of raw materials to ensure high-quality clinker formation. This study investigates the chemical composition of cement raw materials used in clinker formation at BUA Cement Plant Sokoto. The primary aim is to analyze the raw material composition, assess its impact on clinker formation, and develop optimization strategies for improving clinker quality. Chemical analysis was conducted using X-Ray Fluorescence (XRF) Spectroscopy to determine the concentration of major oxides, and X-Ray Diffraction (XRD) Analysis to identify crystalline phases in raw materials and clinker. The collected data were statistically analyzed to establish correlations between raw material variability and clinker mineralogy. Preliminary results indicate that Stockpile 1 exhibits high CaO (49.38%) and CaCO₃ (88.17%), resulting in a high Lime Saturation Factor (LSF) of 1.902, which can lead to excessive free lime and poor clinker grindability. Conversely, Stockpile 4 has moderate CaO (39.69%) and CaCO₃ (70.88%), with higher SiO₂ (15.64%), Al₂O₃ (4.37%), and Fe₂O₃ (2.66%), indicating a balanced composition but requiring additional limestone to optimize LSF. The combined analysis suggests that blending these stockpiles could improve clinker quality. Further analysis of raw mill and clinker compositions confirmed that high-quality clinker is directly linked to optimized raw mix proportions. Based on these findings, optimization strategies such as raw material blending, composition adjustments, and alternative material incorporation are recommended to enhance clinker formation efficiency and reduce production costs.

KEYWORDS: Chemical, Clinker, Grindability, Composition, Analysis

1. Introduction

Cement is a hydraulic binder forming a paste when mix with water. It is the most used construction material in the world (Telschow, 2012). The production process in cement manufacturing plant is typically energy intensive and requires large amount of resources (Cantini and Marti, 2021). The production of cement has several procedures, which include raw materials blending process, clinker production process; clinker grinding process and packaging process (S. Nuhu et al, 2023). Its production depends heavily on the quality of raw materials used for clinker formation. Clinker is the primary product formed in the cement making process, and its composition determines the quality and performance of the final cement. The chemical composition of the raw materials such as limestone, clay, and additives influences the efficiency of clinker production and its resulting properties. The primary components of raw materials used in clinker production consist of four key oxides: calcium oxide (CaO), silica (SiO₂), alumina (Al₂O₃), and iron oxide (Fe₂O₃). The quality of the clinker is largely determined by these oxides. Additionally, the proportion of these components in the raw materials significantly influences the characteristics and quality of the cement clinker. Achieving an optimal balance of these ingredients enhances and stabilizes the quality of cement, making it essential to properly mix the raw materials (kiln feed) (Li et al., 2012). The optimal ratio of ingredients is essential for promoting and stabilizing cement quality, making it crucial for cement raw materials (kiln feed) to be adequately blended process (Nuhu et al, 2023). The production of cement clinker primarily requires two natural raw materials: calcium carbonate (limestone) and aluminum silicate (such as clay or shale). These materials complement each other in stoichiometric proportions to form the necessary compounds or phases in the clinker in the desired quantities. When the primary raw materials do not meet the required stoichiometric ratio, corrective materials like laterite, iron ore, bauxite, sand, or sandstone can be added to achieve the desired chemical composition of the raw mix

(Marroccoli et al., 2010). The ideal concentration of calcium carbonate (CaCO₃) in the kiln feed should range between 74-76%, as this range facilitates a softer burning process in the kiln, resulting in good clinker formation and lower energy consumption (Aldieb and Ibrahim, 2010). The four primary oxides (CaO, SiO₂, Al₂O₃, and Fe₂O₃) present in the raw materials are crucial to the efficiency of cement plants. Understanding the chemical properties and proportions of raw materials is essential for optimizing the clinker formation process and ensuring high quality cement. This research aims to study the chemical composition of cement raw materials, their impact on clinker formation, and suggest improvements to enhance production efficiency.

1.2 Research Problem Statement

Despite advances in cement production technology, the variation in the chemical composition of raw materials remains a significant challenge. The variability can lead to inconsistent clinker quality, higher energy consumption, and increased costs. This research seeks to address the chemical composition of raw materials used in clinker formation, the variation in the composition of raw materials affect clinker properties and cement quality and suggest optimization methods that can be implemented to ensure the consistent chemical composition of raw materials.

1.3 Research Aim and Objectives

1.3.1 Aim

The aim of this research, is to study the chemical composition of cement raw materials for clinker formation case study BUA Cement Plant Sokoto

1.3.2 Objectives

- a) To analyze the chemical composition of raw materials used in clinker production.
- b) To examine the impact of variations in raw material composition on clinker formation.
- c) To develop optimization strategies for achieving consistent raw material

composition for efficient clinker production.

2.1 Brief History on Cement Discovery

Cement is a product obtained by pulverizing clinker formed from raw materials primarily consisting of lime (CaO), silicate (SiO_2), alumina (Al_2O_3) and (Fe_2O_3) iron oxide. When it is mixed with water it forms paste which hardens and binds aggregates (sand, gravel, and or crushed rock together to form a hard durable mass called concrete). Cement is the world's most widely used construction material and is a key ingredient in concrete. The cement manufacturing process includes the raw-materials blending and burning process, the cement clinker grinding process, and the packaging process. One of the main processes that affect cement quality is the raw material blending process. The task of this process is to mix a variety of materials such as limestone, shale, sandstone, and iron, to produce cement raw meal for the kiln (Tiryaki et al., 2016).

2.2 Cement Manufacturing Process

The production of cement takes place through the following processes; preparation of raw materials, production of cement clinker, preparation of cement and its packaging. The raw materials for Portland cement production are mixture of fine powder in the dry process the major oxides are calcium oxide, silicon oxide, aluminium oxide, ferrite oxide while the minor oxides are magnesium oxide, nitrogen and tin oxides which are negligible (Rikoto and Nuhu 2019). The raw materials are usually quarried from local rocks. At some deposit locations, the raw materials already contain the desired composition, but in other places they require addition of clay and limestone, as well as iron ore (Alemayehu and Sahu, 2013).

2.2.1 Limestone quarrying and stockpiling

Quarrying of limestone is a process by which sedimentary rock is removed from ground using different methods. At BUA Sokoto Cement Plant, the raw material is removed from the local source by the method of excavation i.e using the excavators and other heavy equipment, as shown in Figure 2.1. After being excavated, the dump trucks transfer the raw material to the crushing

unit. The aim of crushing is to meet a certain particle size reduction of 15 to 20 mm and proportioning which enables easy handling of material in the mill. With help of tripper and belt conveyor, the raw materials (crushed limestone) are arranged into different stockpiles. The type of stocking method done is the chevron stocking. In this type of stocking, material is built up in layers from a drop point which moves continuously back and forth along the centre line of the stockpile (Taylor and Francis, 2018).

The raw material stored in a particular hopper is based on the percentage of calcium carbonate (CaCO_3) percent in the raw material.

At $\text{CaCO}_3 \leq 74\%$, i.e. low grade limestone,

At $\text{CaCO}_3 \geq 75\%$, i.e. high grade limestone.

With these grades of limestone, there is an arrangement four hopper i.e two high grade and two low grade hoppers. For a good kiln feed, a target of approximately 75% CaCO_3 is needed. To reach this target, a raw feed blending system is introduced with the help of a weigh feeder system.

2.2.3 Raw Feed Milling

The aim of raw milling is to produce the required quantity of kiln feed which has the sufficient burnability for stable and economic kiln operation and which will produce a marketable product with consistent quality. With dry process operation, the raw mill stage normally includes drying feed to a moisture content less than 1% to permit trouble free handling and helps in maximizing fuel economy and lowest production cost will be achieved.

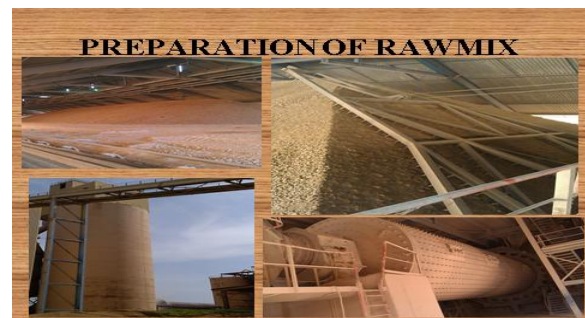


Figure 2.2: Some equipment at crusher and raw mill section.

The homogeneity of raw mix chemical composition has an important relationship to:

- a) Fuel consumption
- b) Kiln operation
- c) Clinker formation

The most important control properties for raw mill product are:

- a) Raw feed chemistry
 - ⇒ Chemical composition: $\text{CaO}_3, \text{SiO}_2, \text{Fe}_2\text{O}_3$ and Al_2O_3
 - ⇒ Calculated mineralogy: $\text{C}_2\text{S}, \text{C}_3\text{S}, \text{C}_3\text{A}$, and C_4AF
 - ⇒ Calculated ratio: LSF, SM and AM
- b) Raw feed fineness

This is important because it allows for alite formation reaction to occur during pyroprocessing, without causing the kiln to have a record of “poor burnability”. Fineness is usually assessed on a 200 μm and 90 μm sieve with a residue target and $\leq 3\%$ on 200 μm and that of 90 μm is $\leq 15\%$ respectively

2.4 Clinker Compositional Factors

Clinker compositional factors centered on the composition of oxide are very beneficial in relating the characteristics of Portland clinker. The following factors are broadly used. Chemical formulae denote weight percentages (Telschow, 2012)..

2.4.1 Silica Saturation Factor (SSF)

SSF is the efficiency of the combination of silica with left over lime after forming C_3A and C_4AF . The value is usually sustained between 0.85 and 0.95, and it results in very suitable cement.

$$\text{SSF} = \frac{[\text{CaO} - (1.65\text{AL}_2\text{O}_3 + 0.35\text{Fe}_2\text{O}_3 + 0.7\text{SO}_3)]}{2.8\text{SiO}_2} \quad (1)$$

2.4.2 Silica Modulus (SM)

The silica ratio or modulus is given as:

$$\text{SM} = \frac{\text{SiO}_2}{\text{AL}_2\text{O}_3 + \text{Fe}_2\text{O}_3} \quad (2)$$

SR is usually between 2.0 and 3.0. A high silica ratio shows that extra calcium silicates exist in

the clinker and a lesser amount of ferrite and aluminate (Sanusi et al., 2020).

2.4.3 Alumina Modulus (AM)

Alumina Modulus is given as:

$$\text{AM} = \frac{\text{AL}_2\text{O}_3}{\text{Fe}_2\text{O}_3} \quad (3)$$

The proportions of aluminate and ferrite in a clinker sample are determined by this ratio. A decrease in AR would mean that there would be relatively more ferrite and less aluminate in the clinker and vice versa (Bentz, 1997)

2.4.4 Lime Saturation Factor (LSF)

LSF is a ratio of CaO to the three other key oxides. In relation to clinker, it is calculated as:

$$\text{LSF} = \frac{\text{CaO} * 100}{2.8\text{SiO}_2 + 1.2\text{AL}_2\text{O}_3 + 0.65\text{Fe}_2\text{O}_3} \quad (4)$$

LSF controls the proportion of C_3S in the clinker. A clinker having a high ratio of C_3S to C_2S will have a high LSF and vice versa. LSF having value close to or beyond 1.0 indicates a likelihood of the presence of free lime (FCaO) in the clinker. This is due to the fact that at LSF 1.0, all free lime present would have combined with C_2S to form C_3S . If the value of LSF is greater than 1.0, the excess free lime would have nothing to combine with and will therefore remain as free lime. The significance of LSF is that it takes into account the possible combining power of Al_2O_3 , SiO_2 , and Fe_2O_3 with CaO. LSF in Portland cement should within 0.66 and 1.02. If it is relatively close to, or around 1.0 in a clinker sample, it will be very hard to burn the clinker adequately. Therefore, it is much better to remain the value at 0.9 (kebede 2010).

2.5 Production of Clinker

CaO , SiO_2 , Al_2O_3 and Fe_2O_3 are the major components of cement clinker, they account for more than 95%. MgO , TiO_2 , P_2O_5 and alkalis are the minor components in total less than 3% and are not present in individual oxide, but exist as compounds formed by two or more oxides (Aldieb and Ibrahim, 2010). Clinker is formed in the kiln from reactions between the four main

raw material components, which are shown in the Table 2.2.

Table 2.1: Raw Material Chemistry

Material	Chemical name	Formula	Shortened name	Typical source
Limestone	Calcium carbonate	CaCO_3	-	Limestone, chalk
↓	↓	↓	Limestone must be heated in the kiln to form lime before it can react`	
Lime	Calcium oxide	CaO	C	
Alumina	Aluminium oxide	Al_2O_3	A	Clay, bauxite, fly ash
Iron oxide	Iron oxide	Fe_2O_3	F	Iron ore,
Silica	Silica oxide	SiO_2	S	Sand, shale, clay

Sources: (Telschow, 2012)

The short names given to these oxides (S, A, F and C) are used by cement chemists when referring to clinker chemistry. When limestone is converted to lime in the Kiln, the four oxides can react to form the clinker minerals which give cement its properties.

3.0 MATERIALS AND METHODS

3.1 Sample Collection

The data of the raw material and clinker chemical composition will be obtain from BUA Cement Plant Sokoto, after the raw materials undergo chemical analysis using the following techniques:

- X-Ray Fluorescence (XRF) Spectroscopy** to determine the concentration of major oxides (CaO , SiO_2 , Al_2O_3 , Fe_2O_3 , MgO , SO_3 , etc.)
- X-Ray Diffraction (XRD) Analysis** to identify and quantify crystalline phases in raw materials and clinker.

3.2 Data Analysis and Interpretation

The chemical composition data will be statistically analyzed to determine the correlation between raw material composition and clinker phases. The study will focus on the variability in composition and its effect on clinker mineralogy.

3.3 Optimization Approach

Based on the findings, recommendations will be made to optimize raw material composition. This may include adjusting the proportions of materials, blending techniques, or introducing alternative raw materials to improve clinker quality and reduce production costs.

4.0 Results and Discussion

Table 4.1 Chemical Composition of Raw Materials

Compositions	Stockpile 1	Stockpile 4	Raw Mill	Clinker
CaO	49.38	39.69	41.66	64.00
SiO ₂	8.08	15.64	13.38	20.60
Al ₂ O ₃	2.10	4.37	3.40	5.41
Fe ₂ O ₃	1.25	2.66	2.30	3.78
MgO	1.05	1.94	1.32	2.03
CaCO ₃	88.17	70.88	74.40	
LSF	1.902	0.782	0.968	0.961
SM	2.41	2.22	2.35	2.24
AM	1.68	1.64	1.48	1.43

Table 4.1 shows the data of raw materials chemical compositions. In Stockpile 1, the result shows high CaO (49.38%) and CaCO₃ (88.17%), which Indicates a dominant limestone component. Excessive CaO results in a very high LSF (1.902), which can lead to free lime and poor clinker grindability. Low SiO₂ (8.08%), Al₂O₃ (2.10%), and Fe₂O₃ (1.25%), this Shows insufficient siliceous and aluminous material for clinker mineral formation. SM (2.41), this Falls within the acceptable range for silicate formation but is slightly high, indicating less Al₂O₃ and Fe₂O₃. AM (1.68), hence indicates good clinker mineral reactivity. In

Stockpile 4, there is moderate CaO (39.69%) and CaCO₃ (70.88%) Suggests balanced composition but with lower lime content compared to Stockpile 1. Higher SiO₂ (15.64%), Al₂O₃ (4.37%), and Fe₂O₃ (2.66%): Indicates clay or siliceous materials, complementing. LSF (0.782): Lime under saturation, requiring additional limestone to balance. SM (2.22) and AM (1.64), which all are within the optimal ranges. Hence, the stockpile 1 and stockpile 4 complement each other, with Stockpile 1

Table 4.2 Raw meal and clinker composition

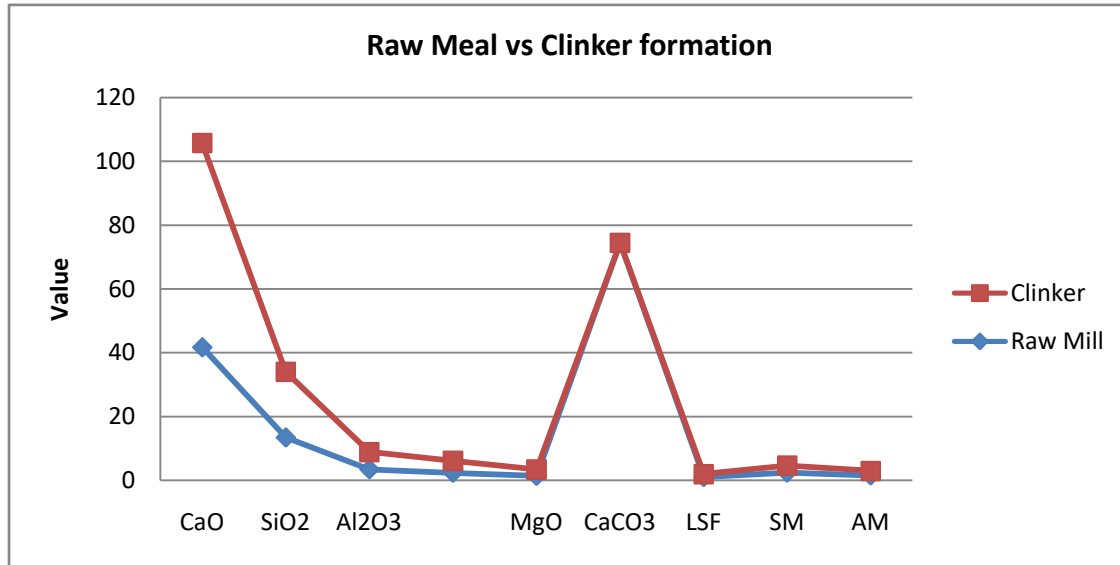
Compositions	Raw Mill	Clinker
CaO	41.66	64.00
SiO ₂	13.38	20.60
Al ₂ O ₃	3.40	5.41
Fe ₂ O ₃	2.30	3.78
MgO	1.32	2.03
CaCO ₃	74.40	
LSF	0.968	0.961
SM	2.35	2.24
AM	1.48	1.43

Table 4.2 presents the chemical composition of both the raw mill product and the resulting

clinker. According to the literature, the quality of clinker is highly dependent on the composition and consistency of the raw mill

product. Proper raw material proportioning and homogenization in the raw mill ensure an optimal balance of oxides, which is crucial for clinker mineral formation. Any deviation in the raw mill composition can significantly affect the

clinker quality, leading to issues such as free lime, poor grindability, or undesirable phase formation. Therefore, maintaining a well-optimized raw mill product is essential for producing high quality clinker.



Based on the analysis of the raw meal and clinker composition, the following observations were made:

a) Calcium Oxide (CaO): The CaO content increases from 41.66% in the raw meal to 64.00% in clinker due to the thermal decomposition of calcium carbonate (CaCO₃) during the calcination process. According to Muhammad and Ibrahim (2010), the transformation facilitates the formation of calcium silicates, primarily dicalcium silicate (C₂S) and tricalcium silicate (C₃S), which are essential for cement strength development.

b) Silicon Dioxide (SiO₂): SiO₂ concentration rises from 13.38% in the raw meal to 20.60% in clinker, as it reacts with CaO to form C₂S and C₃S, which contribute to the cement's binding properties and long-term strength.

c) Alumina (Al₂O₃) and Iron Oxide (Fe₂O₃): These oxides play a critical role in the formation of tricalcium aluminate (C₃A) and tetracalcium aluminoferrite (C₄AF), which

d) Magnesium Oxide (MgO): The MgO content increases from 1.32% in the raw meal to 2.03% in clinker. While MgO contributes to clinker formation, excessive levels can lead to unsound cement if not properly controlled.

e) Lime Saturation Factor (LSF): The LSF values of 0.968 in the raw meal and 0.961 in clinker indicate optimal lime content for clinker formation, ensuring efficient reactions while minimizing the risk of excessive free lime, which could affect cement quality (Atmaca et al., 2014).

f) Silica Modulus (SM) and Alumina Modulus (AM): The slight variations in SM

(from 2.35 to 2.24) and AM (from 1.48 to 1.43) suggest a well balanced chemical composition. These values ensure proper clinker mineralogy, stable cement properties, and good workability of the final product.

This analysis highlights the importance of maintaining an optimized raw meal composition to achieve high quality clinker and, consequently, superior cement performance.

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