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Optimization of Kiln Feed Chemical Composition for Clinker Formation in BUA Sokoto Cement Plant

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ABSTRACT

Inappropriate chemical composition of cement raw materials has significant impact on the cost of cement production, and clinker formation. This paper presents optimization of the kiln feed chemical compositions for clinker formation with minimum cost, while fulfilling the critical clinker quality parameters. Mathematical model that relates raw material and fuel mix chemistry to clinker chemistry was developed and solved using linear programming method to achieve the objective. The study considered BUA Cement Plant Sokoto, as a case study. It has 5 types of feed materials with different limestone quality grades grouped into stockpiles 1, 2, 3, 4 and 5 with the fifth stockpiles being a corrected material. Based on the linear programming simulation, the optimized kiln feed was achieved at the cost of $12.63 per ton of kiln feed with 74.90% of limestone, which when compared with the corresponding production cost from the company for the same feed obtained to be $15.71 per ton with 76.31 % of limestone. With 74.90% of limestone is expected to lead to a saving of $3.08 per ton of kiln feed. The clinker quality parameters achieved from this study are 97.26% of lime saturation factor (LSF), 2.45% of silica modulus (SM) and 1.56% of alumina modulus (AM), which satisfied the industrial quality standard. The clinker minerals corresponding to these parameters were calculated to be 63.17% of C_3S, 11.21% of C_2S, 8.57% of C_3A and C_4AF. The results obtained show that the models can minimize the raw material cost without trading-off the clinker quality.

1. INTRODUCTION

Cement is a hydraulic binder forming a paste when mix with water. It is the most used construction material in the world. Cement original materials are usually the limestone, shale, sandstone, clay and corrected material. The production of cement has several procedures, which include raw materials blending process, clinker production process; clinker grinding process and packaging process (Rikoto and Nuhu, 2019).

Kiln is the heart of the cement manufacturing, is the stage at which finely grounded and well blended raw materials (kiln feed) undergo a chemical transformation at the temperature of 1450 to form a new compound called clinker (Nuhu et al., 2022). The quality of cement raw material and cement clinker can be evaluated by the cement lime saturation (LSF), silica modulus (SM), alumina modulus (AM). LSF, SM and AM are directly determined by the lime, silica, alumina and iron oxides which are contained in cement raw material.

The Kiln Feed is a well-blended raw material that have the sufficient percentage Calcium Carbonate ($CaCO_3$), Silica Modulus (SM), Alumina Modulus (AM) and LSF. The optimum chemical composition of kiln feed must be ranged 74-76% of calcium carbonate ($CaCO_3$). This range gives soft burning in the kiln, good clinker formation with less energy consumption (Aldieb and Ibrahim, 2010). The current existing method practicing at BUA Cement Plant Sokoto used to formulate the raw mix design is based on iterative laboratory trials, which is time consuming and heavily relies on the chemist's experience. The aim of this research work was to optimize the kiln feed chemical composition for clinker formation in BUA Sokoto Cement Plant.

The preparation of good kiln feed is an important step in cement manufacturing process. Producing a good quality clinker depends heavily on it. In general, the feed introduced into the rotary kiln consists of 80 % of calcium carbonate (CaCO) and 20% of clay (SiO_2, Al_2O_3, Fe_2O_3 and H_2O etc) (Besulandu and Marias, 2019). The cement factory may have to correct the contents. The overall composition is sometimes adjusted to meet the requirements of the type of cement to be produced. The transformation of kiln feed into clinker takes place through many chemical reactions that involving the following compounds: $CaCO_3$, CaO, SiO_2, Al_2O_3, Fe_2O_3, $(CaO)_2.SiO2$, $(CaO)_3.Al_2O_3$, $(CaO)_4.Al_2O_3.Fe_2O_3$. Some compounds are often neglected because they are considered as minor elements with low levels (Tiryaki et al., 2016). The production of quality cement is possible only if the composition of the mixture of raw materials is made optimally. Bisulandu and Marias (2019), gave the limit values which the limestone-clay mixture finely ground must satisfy.

Previously, many researchers have studied and published papers on various cement processes in cement production. In Barath et al., 2022, work on Optimization of raw mix design of clinker production, they developed an optimization models, to obtain the best mix proportion with minimum cost, mathematical models were also developed to obtain the clinker composition, they raw material chemical composition was generated from the models. In Li et al. (2012) work on modeling and optimization of cement raw materials blending process they developed a general nonlinear time-varying model of the raw material blending process but didn't give much attention on the kiln feed (raw mix) critical production parameters. All the previous researches didn't give much attention to modeling of raw material chemical composition and obtaining optimum percentage of $CaCO_3$. It was reported that, the optimum chemical composition of kiln feed (raw mix), must be ranged 74-76% of calcium carbonate ($CaCO_3$). This range gives soft burning in the kiln, good clinker formation with less energy consumption (Aldieb and Ibrahim, 2010). This work presented an optimization of the kiln feed chemical compositions for clinker formation with minimum cost, while fulfilling the critical clinker quality parameters. The objectives of this research include; Formulation of raw mix optimization models to obtain the mix proportion with minimum cost, development of mathematical equations to obtain the clinker chemistry and calculation of the critical cement craft parameters and mineral phases (LSF, SM, and AM). The study considered the BUA Cement Plant, Sokoto, Nigeria as a case study. It has five types of feed materials with different limestone quality grades grouped into stockpiles 1, 2, 3, 4 and 5 with the fifth stockpiles being a corrected material. Each raw material sample was collected and analyzed using X- ray diffraction (XRD) analyzer machine, to determine the chemical composition of the materials.

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2. MATERIALS AND METHODS

2.1. Data and Software Used

The data and software used included data of the raw materials' chemical composition, chemical composition of the fuel ash, process operating condition data from the lab, MATLAB software and Microsoft excel.

Table 1: Notation of chemical composition of the raw materials

Material type (tons)	Mass of chemical compositions oxides in stockpiles					Cost/ton
	SiO_2	CaO	Al_2O_3	FeO_3	MgO	
Stockpile 1, X_1	ω_1	γ_1	Γ_1	μ_1	ρ_1	C_1
Stockpile 2, X_2	ω_2	γ_2	Γ_2	μ_2	ρ_2	C_2
Stockpile 3, X_3	ω_3	γ_3	Γ_3	μ_3	ρ_3	C_3
Stockpile 4, X_4	ω_4	γ_4	Γ_4	μ_4	ρ_4	C_4
Corrected Material X_5	ω_5	γ_5	Γ_5	μ_5	ρ_5	C_5

Where

X_1, X_2, X_3, X_4 and X_5 represent the mass of stockpiles in the raw mill
ω_1 to ω_5 represent the mass of silica content in stockpile 1, 2, 3, 4, and 5 respectively
γ_1 to γ_5 represent the mass of Lime content in stockpile 1, 2, 3, 4, and 5 respectively
Γ_1 to Γ_5 represent the mass of Alumina content in stockpile 1, 2, 3, 4, and 5 respectively
μ_1 to μ_5 represent the mass of Iron content in stockpile 1, 2, 3, 4, and 5 respectively
ρ_1 to ρ_5 represent the mass of Magnesium content in stockpile 1, 2, 3, 4, and 5 respectively
C_1 to C_5 represent the cost raw material per stockpile
The objective function is expressed as:

$$Minimize\ cost = \sum_{i=1}^{n} C_i X_i \quad (1)$$

$$\frac{Cost}{ton}\ x\ ton\ \ = Cost$$

Where C_i is the cost/ton, $X_i$is the material type & n is the number of samples (stockpile)

2.2. Formulation of the Optimization Models in Linear Programming

The linear programming problem was formulated as follows:

$$(X_1)(\gamma_1)+(X_2)(\ \gamma_2)+(X_3)(\ \gamma_3)\ +(X_4)(\ \gamma_4)+(X_5)(\ \gamma_5) = C_{RM} \quad (2)$$

$$(X_1)(\omega_1)\ +(X_2)(\ \omega_2)+(X_3)(\ \omega_3)+(X_4)(\ \omega_4)+(X_5)(\ \omega_5) = S_{RM} \quad (3)$$

$$(X_1)(\Gamma_1)\ +(X_2)(\ \Gamma_2)+(X_3)(\ \Gamma_3)+(X_4)(\ \Gamma_4)+(X_5)(\ \Gamma_5)X5 = A_{RM} \quad (4)$$

$$(X_1)(\mu_1)+(X_2)(\ \mu_2)+(X_3)(\ \mu_3)+(X_4)(\ \mu_4)+(X_5)(\ \mu_5) = F_{RM} \quad (5)$$

$$(X_1)(\rho_1)+(X_2)(\ \rho_2)+(X_3)(\ \rho_3)+(X_4)(\ \rho_4)+(X_5)(\ \rho_5) = M_{RM} \quad (6)$$

2.2.1. Development of mathematical equations to obtain the clinker chemistry

The conversion from raw mix chemical composition to clinker chemical composition can be done by multiplying it by loss on ignition factor (LOI). The loss on ignition can be determined by test in a laboratory furnace (Barath et al, 2022).

The formula to calculate the loss on ignition factor is:

$$\text{LOI factor} = \frac{1}{1-\frac{LOI}{100}} \quad (7)$$

Then, the contribution of chemical oxide of both raw mix and fuel mix that transform into clinker phases are as follows:

$$((C_{RM}) \text{ x Loss Factor x } \frac{99.5}{100}) + \left((C_{Ash})x\frac{0.5}{100}\right) = C_{Ckr} \quad (8)$$

$$((S_{RM}) \text{ x Loss Factor x } \frac{99.5}{100}) + \left((S_{Ash})x\frac{0.5}{100}\right) = S_{Ckr} \quad (9)$$

$$((A_{RM}) \text{ x Loss Factor x } \frac{99.5}{100}) + \left((A_{Ash})x\frac{0.5}{100}\right) = A_{Ckr} \quad (10)$$

$$((F_{RM}) \text{ x Loss Factor x } \frac{99.5}{100}) + \left((F_{Ash})x\frac{0.5}{100}\right) = F_{Ckr} \quad (11)$$

$$((M_{RM}) \text{ x Loss Factor x } \frac{99.5}{100}) + \left((M_{Ash})x\frac{0.5}{100}\right) = M_{Ckr} \quad (12)$$

2.2.2. Clinker minerals

The cement clinker mainly consists of four phases (minerals), namely alite (C_3S), belite (C_2S), tricalcium aluminate (C_3A) and tetracalciumaluminoferrite (C_4AF) (Barath et al, 2022). C, S, A and F in the clinker mineral, represent as CaO, SiO_2, Al_2O_3,and Fe_2O_3 respectively, it also have the small proportion of voids where the free lime (FCaO) and free MgO are present without combining with the other phases. The main clinker minerals compositions are then calculated through the application of Bogue equations (Barath et al, 2022)

$$C_3S = 4.07((C_{ckr}) - FcaO) - 7.60(S_{ckr}) - 6.72(A_{ckr}) - 1.43(F_{ckr}) - 2.85(S_{Ash}) \quad (13)$$

$$C_2S = 2.87(S_{ckr}) - 0.754C_3S \quad (14)$$

$$C_3A = 2.65(A_{ckr}) - 1.69(F_{ckr}) \quad (15)$$

$$C_4AF = 3.04(F_{ckr}) \quad (16)$$

When limestone is converted to lime in the kiln, the four oxides can react to form the clinker minerals which give cement its properties.

The four main clinker minerals made in the kiln are:

a) Ferrite C_4AF) -Tetra calcium alumina ferrite $4CaO.Al_2O_3.Fe_2O_3$
b) Aluminate C_3A) - Tricalcuim aluminate $3Ca.Al_2O_3$
c) Belite (C_2S) -Dicalcuim Silicate $2Ca.SiO_2$
d) Alite (C_3S) -Tricalcuim silicate $3Ca.SiO_2$

The materials are designated for short as C_3S,C_2S,C_3A and C_4AF respectively.

2.3. Control Parameters

The critical cement craft parameters such as Lime Saturation Factor (LSF), Silica Modulus (SM), and Alumina Modulus (AM) are the control parameters for the clinker quality target (Barath et al, 2022).

2.3.1. Lime saturation factor (LSF)

The lime saturation factor expresses the ratio between the lime present in the mixture and the amount of lime capable of combining with the silica to form C_3S and C_2S. For technical purposes good values ranged from 0.85 to 0.98 (Nuhu et al., 2020). When the lime saturation factor is greater than 100 %, there is imbalance between the constituents (Nuhu et al. 2020).

$$LS = \frac{C_{ckr}}{2.8S_{ckr}+1.18A_{ckr}+0.65F_{ckr}} \quad (17)$$

2.3.2. Silica Modulus (SM)

The melt phase in the burning zone is a function of silica modulus. When SM is high the amount of melt is low. Therefore, when the SM is too high the formation of nodules and chemical reaction may be too slow making it difficult to operate (Alemayehu and Sahu, 2013). It can be calculated using the formula:

$$\mathrm{SM} = \frac{S_{ckr}}{A_{ckr} + F_{ckr}} \tag{18}$$

Silica modulus is one of the main properties of C_2S (belite) and C_3S (alite), which make up the liquid phase and help in alite formation (Nuhu et al., 2020) Silica modulus usually ranges from 2.0 to 2.7 this ranges gives a better burnability and hence lead to good formation of clinker with lowest possible cost of operation, it also the formation of liquid phase. Liquid phase is important as it led to formation of coating ring inside kiln.

2.3.3. Alumina modulus (AM)

Alumina modulus is also used as an indicator of burning temperature and flux characteristic in the Kiln. It is the measure of the proportion of alumina to iron oxide in the mix, it allows to estimate the ratio of Al_2O_3 and Fe_2O_3 in the mixture. It can be calculated using the formula (Telschow, 2012).

$$\mathrm{AM} = \frac{A_{ckr}}{F_{ckr}} \tag{19}$$

The values of alumina modulus are usually in the range from 1.5 to 2.5. The modulus determines the compositions of liquid phase in the clinker, when it is lower than 1.5 both oxides are present in their molecular ratios and therefore only tetracalciumaluminoferrite can be formed in the clinker. (Mohamed Ibrahim, 2010). Earlier formation of liquid phase or flux in the kiln allows alite formation to start sooner and go for a longer time, which improve the conversion of belite into alite.

Model assumptions

The following assumptions were considered in the formulation for simplicity:

1. All minor oxides are negligible except the magnesium oxide (MgO)

2. The free lime content in the clinker is 1.55%

3. Fuel ash absorption is assumed to be 0.5% and the remaining 99.5% which would be use to obtain clinker chemistry

2.4. 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). They are types of clinker minerals formed in the kiln depend on how much of each raw material is present in the raw mix. Decreasing or increasing the raw material proportions affects both the process and the production. Examples are shown in Table 2.

Table 2: Possible effect of changing raw mix consumption (Aldieb and Ibrahim, 2010)

Change to raw mix	Effect on process	Effect on product
Less lime	Easier burning – less fuel, more clinker, and longer brick life. Harder to grind, lower cement mill output	Less early strength but higher late strength and longer setting time
Less silica (as sand)	Harder burning, more fuel, dusty clinker, shorter brick life but easier milling	Less very early strength lower heat of hydration better sulphate resistance
Less alumina	Harder burning, more fuel, dusty clinker, shorter brick life but easier milling	Less very early strength and heat of hydration, better sulphate resistance.
Less iron oxide	Harder burning, more fuel, smaller clinker nodules and easier milling	Lighter colour red clinker.

3. RESULTS AND DISCUSSION

Table 1 represent the current data of raw material chemical composition obtained based on iterative laboratory trials from the quality control department (laboratory) of the factory. The data shows the chemical compositions of different stockpile including the corrected material, and cost per ton of raw mix. From their analysis they were able to determine $15.71 per raw mix with 76.31% of calcium carbonate quality. 76.31% of calcium carbonate are within the industrial standard as it was captured in the literature review. Table 2 represents the optimization results after the simulation, the following gives the summary description of MATLAB simulation algorithm used in optimization of kiln feed composition (proportion of raw mix). In the first line of the MATLAB code, we define the optimization problem. In lines 2 – 6, we define the stock of the raw materials that we got from lab practical. Next, we define a variable X which denote the raw material. After solving the optimization equations using dual-simplex method the results were obtained to be $12.63 per tons of kiln feed (raw mix) with 74.90 % of limestone quality, clay was determined to be 21.84% and 3.2% of corrected material.

Table 1: Chemical composition of raw material

Materials	Stockpile 1 (Tons)	Stockpile 2 (Tons)	Corrected material (Tons)	Stockpile 3 (Tons)	Stockpile 4 (Tons)	Calculated results	Cost ($)
Compositions (%)	0	26	0	74	0	100	
CaO	42.50	43.66	9.98	38.98	38.10	40.20	12.53
SiO_2	11.05	11.71	45.93	14.18	16.98	13.54	11.98
Al_2O_3	3.02	3.43	13.49	4.57	4.78	4.27	12.78
Fe_2O_3	2.70	2.09	13.30	3.23	2.94	2.93	13.67
MgO	1.58	1.42	13.84	1.93	1.94	1.80	27.60
$CaCO_3$	85.67	86.22	17.82	72.45	68.32	76.31	15.71

Table 2: Simulated result for the mix proportion

Decision variable	Description	Raw mix proportion	Proportions (%)
X_1	Limestone	0.749	74.900
X_2	Sand	0.000	0.000
X_3	Clay	0.218	21.840
X_4	Shale	0.000	0.000
X_5	Corrected	0.033	3.260
Total		1.000	100

Based on the optimization model, the chemical composition of raw materials was used to calculate the clinker chemistry. Equations (8) to (12) were used to compute the clinker chemistry as obtained in Table 3. Table 4 presents to the remaining information that needs to be identified in the linear programming which is associated with the mathematical calculation to convert raw material chemical composition to clinker chemistry. Table 5 represent the results of critical craft parameter, which were obtained using equations (17) to (19). The results indicated that, the parameters are within the target range. Therefore, there is less energy consumption, good clinker formation. As it was mentioned in the literature review that optimum chemical composition of kiln feed must be ranged 74-76% of calcium carbonate ($CaCO_3$). This range gives soft burning in the kiln, good clinker formation with less energy consumption (Aldieb and Ibrahim, 2010). However, the results presented by linear optimization model will only be used when the chemical composition of the raw materials and fuel remains unchanged, which is very difficult (Barath et al, 2022). As the raw material and fuel chemical composition is analyzed based on the random sampling that doesn't represent the whole stockpile. Table 6 represent the clinker minerals/phase and was determined using Equations (13) to (16). In Aldieb and Ibrahim, (2010), it was reported that, alite (C_3S), is the most important constituent in normal Portland cement clinkers. 50-70% range of alite (C_3S), produces most strength up to and including 28 days, belite (C_2S) constitutes 15-30% of normal Portland cement clinkers and this range improves later strength (≥28 days).

Table 3 chemical composition of clinker and fuel mix

	C_{ckr}	S_{ckr}	A_{ckr}	F_{ckr}	M_{Ckr}
1	40.20	19.00	6.00	2.95	6.00
	Fuel Mix 0.5%				
S/N	C_{ASH}	S_{ASH}	A_{ASH}	F_{ASHE}	M_{ASH}
	45.43	23.37	5.67	1.20	4.87

Table 4: Multiplication factor, LOI, and free lime content

Parameters	Values
LOI (%)	36
Factor	1.568
(SO_3)Clk	1.526
Free Lime	1.550

Table 5: Calculated critical cement craft parameter

Clinker minerals	Target	Results
LSF	95-98	97.26
SM	1.9-3.2	2.45
AM	1.5-2.5	1.56

Table 6: Clinker mineral

Clinker minerals	Target (%)	Result (%)
Alite (C_3S)	50 – 70	63.17
Belite (C_2S)	15 – 30	17.21
Aluminate (C_3A)	5 – 10	8.57
Ferrite (C_4AF)	5 – 15	9.82

4. CONCLUSION

This research work, optimization of kiln feed chemical composition of raw material for clinker formation has demonstrated high potential financial gains and can be achieved with the application of linear programming method, through the use of MATLAB, and Excel. After the optimization, the following conclusions were drawn; the current production cost at BUA Cement Plant 1 was determined to be $15.71 per ton of kiln feed (raw mix) with 76.31 % of limestone quality. However, for this study, the production cost was determined to be $12.63 per ton of kiln feed (raw mix) with 74.90% of limestone quality, which when compared will lead to a saving of $3.08 per ton of kiln feed (raw mix). The clinker quality parameters achieved from this study are 97.26% of lime saturation factor (LSF), 2.45% of silica modulus (SM) and 1.56% of alumina modulus (AM), which satisfied the industrial quality standard. The clinker minerals corresponding to these parameters were calculated to be 63.17% of C_3S, 17.21% of C_2S, 8.57% of C_3A and 9.82% of C_4AF. The results obtained show that the models can minimize the raw material cost without trading-off the clinker quality.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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