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Quantitative Optimization of Cement Rotary Kiln for Heat Reduction in Clinker Production

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ABSTRACT: Optimization is the use of specific methods to determine the most cost-effective and efficient solution to a problem or design for a process. In plant operations, benefits arise from improved plant performance, such as improved yields of valuable products, reduced energy consumption, higher processing rates, and longer times between shut downs. This research is concerned with optimization of cement rotary kiln with the aim of reducing heat consumption using Dangote Cement Plant, Obajana as case study. Linear programming method of optimization was adopted, out of which Simplex method of linear programming was used in deriving a simple empirical mathematical model from the related data obtained from sample analysis and pyro processing. The kilns of Dangote cement are designed to consume ≤750Kcal/Kg of clinker but the observed consumption averages between 756 Kcal/Kg - 766Kcal/Kg. The derived mathematical model provides solution from the objective function which gives heat consumption at 739.78 Kcal/Kg of clinker.

Keywords: Heat Energy, Energy Consumption, Clinker, Kiln, Optimization

I. INTRODUCTION

Optimization is the application of specific methods to determining the most cost-effective and efficient solution to a problem or design of a process. In plant operations, the benefits arise from improved plant performance, such as improved yields of valuable output, reduction in energy consumption, higher processing rates, and less shut downs times. In terms of cost, optimization can also lead to reduced maintenance costs, less equipment wear and better staff utilization. In doing this it is very important to systematically identify the objective, constraint and degrees of freedom in the design of a process or a plant that would lead to such benefits as improved quality of design, faster and more reliable troubleshooting, and faster design (Edgar et al, 1988).

In the business of cement manufacturing, the major process of cement production is a highly energy intensive process involving the use of thermal energy and electrical energy. The cost of energy in the production cost of cement is therefore predominantly high and with depleting energy sources and rising energy costs, it is essential for every cement manufacturer to continuously put in effort to reduce the energy consumption in the manufacturing of cement. Therefore, reduced energy consumption will not only help to reduce production cost of clinker, it equally prolongs the lifespan of the equipment (kiln) and also reduces its contribution of greenhouse gases that produces the greenhouse effect on the atmospheric environment (Holderbank cement seminar, 2000).

The cement industry faces increasing pressure for more stringent requirements on profitability, product quality, legislation on emission control and an increasingly competitive market situation. Hence continuous optimization efforts can help in achieving this feat. To optimize the overall performance of a cement manufacturing unit, requires a plant wide automation strategy. Reducing energy demand in all areas must be combined with the search for the optimal operating point that is consistent with productivity and quality targets, and in line with imposed environmental emission limits.

The optimization of the clinker making process is usually done to reduce heat consumption, improve the clinker quality and increase the lifespan of the equipment i.e.the refractory lining, for example, through the stabilizing of process parameters. Doing this will basically require techniques like ensuring optimum raw meal composition, properly managing combustion processes and improving the operation of the cooler. When this is properly done it is expected that;

operating cost of a kiln will reduce, among others, reduce fuel and refractory consumption, lower maintenance costs and then increase productivity of clinker.

I. LITERATURE REVIEW

Cement is described as a material with adhesive and cohesive properties which make it capable of bonding mineral fragments into a compact whole.Many cement manufacturers use dry process method for cement production by applying Low Pour Fuel Oil (LPFO) and natural gas to firing the kiln to generate heat energy required in the kiln for production of clinker from the kiln feed. In modern cement plant, natural gas and fuel oil are preferred for firing the kiln over coal. The main reason being that firing of cement kiln with solid fuel like coal requires installation of capital equipment for drying and grinding of the coal into a fine powder which increases the production cost (Charles and Baukal, 2013).

A. Overview of Cement Making Process

Cement is made of calcareous (limestone, chalk) and argillaceous (clay, shales) materials in the ratio of 3:1. The Calcareous and Argillaceous materials are obtained from the earth and properly proportioned in order to get a suitable composition of Lime (CaO) 65%, Silica (SiO_2) 20%, Alumina (Al_2O_3) 5% and Iron (Fe_2O_3) 3% present in the mixture. These forms the major ingredients while minor constituents like Magnesia (MgO), Sodium,Potassium, Sulphur, Chlorine compounds etc. make up the remaining percentage. These may also be present in the raw materials to limited extent but do not have adverse effect on either the manufacturing process or the quality of cement produced. The Major unit operations involved in cement manufacturing process include, raw materials extraction and preparation, pyro-processing, grinding of cement clinker and packing and dispatch of cement product.

B. Raw Materials Extraction and Preparation

Cement plants are located close to a location of the basic raw materials required for production of cement. The raw materials are limestone, clay (laterite) and gypsum. One of the most important is the limestone and as such, many cement plants are located near high grade limestone deposits. The raw materials are extracted through the process of quarrying and suitable process of size reduction through crushing and grinding for preparation of pulverized raw meal. The pulverized raw meal is then blended in the right proportion for production of good quality cement clinker.

C. Pyro-processing

Pyro-processing is a process in which materials are subjected to high temperatures in order to bring about a chemical or physical change. Pyro-processing includes such terms as ore-roasting, calcination and sintering. Equipment for such processes includes kiln, electric arc furnaces and reverberators.The blended raw meal is heated inkilns that are long rotating steel cylinders on an incline. The meal feed enters at the high end of the cylinder and slowly moves along the length of the kilns. At the low end of the kilns, fuel is injected and burnt, thus providing heat necessary to make the materials react. This process takes up to 30-40 minutes for the mixture to pass through the kiln. When the raw-mix is in its correct proportion,new mineral with hydraulic propertiesis formed upon sintering up to the clinkering temperature of about 1450° C. The clinker formation process can be divided into four main steps:

1. Drying and preheating (20 – 800° C): is the release of free and chemically bound water.
2. Calcination(800 – 1350° C): Decomposition of $CaCO_3$ to CaO and $MgCO_3$ to MgO to release of CO2, initial reactions with formation of clinker minerals and intermediate phases.

$$CaCO3 = CaO + CO2 \quad (1)$$

$$MgCO3=MgO + CO2 \quad (2)$$

$$CaO + Al2O3= CaO.Al2O3 \quad (3)$$

3. Clinkering (1350 – 1550° C): involves formation of calcium silicates,calcium aluminates and liquid phase

$$CaO.Al2O3+2CaO= 3CaO.Al2O3 \quad (4)$$

$$CaO.Al2O3+3CaO+Fe2O3=CaO.Al2O3.Fe2O3 \quad (5)$$

$$CaO.SiO2+CaO=2CaO.SiO2 \quad (6)$$

$$CaO+2CaO.SiO2 = 3CaO.SiO2 \quad (7)$$

4. Kiln internal cooling (1550 – 1200° C): this is where crystallization of calcium silicates, calcium aluminate and calcium aluminoferrite takes place to form clinker nodules before it exits the kiln into a cooler to get it to stable phases. The clinker mostly appears as a dusty granular mixture of dark grey/black particles up to 40mm in size (Tokheim, 1999).

D. Composition of Clinker

The main mineral components in clinker are silicates, aluminates and ferrites of calcium.The balance is made of alkali sulphates and minor impurities and all are subject to wide variation as shown in the Table 1 (Nicholas, 2012).

Table 1: Constituent Compounds of Clinker

Compound	Molecular Formula	Abbreviation	Nomenclature
Tri-Calcium silicate 65%	3 $CaO.SiO_2$	C3S	Alite
Di-Calcium silicate 15%	2 $CaO.SiO_2$	C2S	Belite
Tri-Calcium aluminate 7%	3 $CaO.Al_2O_3$	C3A	Calcium Aluminate
TetracalciumAluminoferrite 8%	4 $CaO.Al_2O_3.Fe_2O_3$	C4AF	Calcium AluminoFerrite

E. Grinding of Cement Clinker

Clinker is ground in mills along with appropriate quantity of gypsum and inert fillers such as limestone for production of finely pulverized cement with desired fineness. Fineness and particle size distributions of the finished product have a strong influence on the cement quality. Blended cements contain other constituents such as granulated blast-furnace slag, natural or industrial pozzolan such as volcanic tuff or fly ash from thermal power plants. Mineral additions in blended cements may either be inter-ground with clinker or ground separately or mixed with Portland cement (Aldridge, 1982).

F. Packing and Dispatch of Cement

Pulverized cement is stored in silos. Depending on customers' requirements, cement is loaded in bulk or in 50kg bags that are packed with the help of conventional rotary packaging or electronic packaging equipment, and finally loaded onto trucks that are dispatched to the customers.

G. Kilns

A kiln is a type of oven with thermally insulated chamber that produces temperatures sufficient to complete some process, such as hardening, drying, or chemical changes. Kilns have been used for millennia to turn objects made from clay into pottery, tiles and bricks. Various industries use rotary kilns for pyro-processing to calcinate ores, calcinate limestone to lime for cement, and to transform many other materials.There are six common types of kiln; wet process kilns, long dry kiln, travelling grate preheater kiln (lepol), cyclone preheater kiln, cyclone preheater kilns with riser duct firing and, precalciner kilns.

H. Heat for Clinker Production

Heat is a form of energy that is transferred from one body to another as a result of difference in temperature. A substance may absorb heat without an increase in temperature by changing from one physical state to another or from one solid form to another usually called a crystalline transition. The units of heat most commonly used are the calorie and British thermal unit (BTU). The appropriate selection and use of fuel has always been and still is a matter of great concern for the cement industry. This essential material is always vital when used in the kiln for clinkering and secondarily in dryers of raw materials or additives, in hot gas generators, etc.

The current competition in the cement market and the high impact of the item "fuel cost" in the final price of the product is making companies look for the most economic mix to fire their kilns. Carbon and hydrogen are the elements that add the greatest energy contribution to the fuel while nitrogen and sulphur not only bring a less significant energy contribution, but they also create products with a high environmental contamination potential (Javed et al, 2004).

I. Characteristics of Fuels

The physical and chemical characteristics of fuels play a major role in the combustion process, in clinker production process, and in emission of atmospheric pollutants. These characteristics vary from fuel to fuel (Charles and Baukal, 2013).

The physical characteristic of a fuel that most influences the firing process is the phase in which it becomes available for combustion. Solid, liquid, and gaseous fuels burn according to different mechanisms and kinetics. Solid fuels are normally pulverized before used and pneumatically transported to the kiln into which they are injected with the conveying air; liquid fuels are always nebulized when they are fired; and gaseous fuels are simply injected into the kiln. Other physical properties of the fuel that are important for establishing its conditions of use are, Specific heat, Thermal conductivity, Density or specific mass, Pour point, Adiabatic Flame Temperature.

Chemical characteristics of a fuel is the immediate and elementary composition that can impact on the heating value, flame adiabatic temperature of the firing mechanisms and the emissions and residue resulting from combustion. The behaviour of fuels depends on whether the fuel is simple i.e. essentially a sole chemical species, or involves multi components i.e. a mix of several chemical species. Multi component fuels show different firing behaviour from those formed by a sole chemical species.

J. Optimization byLinear Programming

Optimization by mathematical programming is the use of specific methods to determine the most cost-effective and efficient solution to a problem or process design.This technique is one of the major quantitative tools in industrial decision making. A wide variety of problems in the design, construction, operation and analysis of plants can be resolved by optimization. There are many types of optimization models namely; linear programming, non-linear programming, multi-objective programming, and bi-level programming.Linear programming problems consist of a linear objective function (consisting of a certain number of variables) which is to be minimized or maximized subject to a certain number of constraints. The constraints are linear inequalities of the variables used in the objective function. Linear programming is closely related to linear algebra; the most noticeable difference is that linear programming often uses inequalities in the problem statement rather than equalities (Taha, 2007) and the method most frequently used to solve linear programming is the simplex method (Charnes and Cooper, 1957).

K. Simplex Method of Solving Linear Programming

The simplex method has two basic steps, often called “phases.” The first phase is to find a feasible solution to the problem. After a feasible solution to the problem is found, the simplex method works by iteratively improving the value of the cost function. This is accomplished by finding a variable in the problem that can be increased, at the expense of decreasing another variable, in such a way as to effect an overall improvement in the cost function (Mark, 1998). The following parameters are commonly used for heat optimization based on their importance

1. Particle-size also called residue of the material greatly affect raw-mix burnability. Burnability which is the readiness with which raw-mix is transformed into clinker component minerals during high temperature treatment. The higher the particle-size with greater surface area, the easier it is to sinter and lower heat consumption is achieved. The maximum permissible particle-size of raw-mix is 2.0% on 200μm and 16% on 90μm sieves. To improve on burnability of raw-mix it is desired to reduce the coarse particles which can be achieved by finer grinding (FLSmidth Institute, 2006).
2. Chemical composition. The chemical parameters of significance are lime saturation factor (LSF), and silica modulus (SM). An increase in LSF and SM will result in higher heat consumption. This is determined using X-ray fluorescence (XRF), which identifies and quantifies chemical compounds. LSF may be maintained at 94 % (± 0.5) while SM be kept at 2.4 % (± 0.05) (Alsop et al, 2007). Others such as false air within the system and material retention time may also be considered. In addition to particle-size, both the lime saturation factor and the amount of liquid phase in the raw-mix at the burning temperature influence burnability. Knowing the effect of particle-size on burnability, the effect attributable to chemical composition can be determined (FLSmidth Institute, 2006).

II. MATERIALS AND METHODS

A. Material and Data Collection

Raw mix that consist of limestone, clay and laterite were collected as representative sample of Obajana cement factory. Natural gas was obtained for burning the raw mix and data of quality control analysis and daily production parameter of Obajana cement factory were used to carry out this research. Two model kilns namely kiln A2012 and kiln B2015 with Distributed Control System (DCS) made by FLSmidth, Germany, was used for analysis and computation. Otherequipment used for analysis are X-Ray Florescence Machine, Hosokawa Alpine Sieve Machine, Electronic Weighing Balance and a Ring-shaped Pelletizer. Sieving and chemical analysis were carried out in the laboratory using Hosokawa Alpine sieve machine, weighing balance, ring-shaped pelletizer and an X-ray florescence machine to obtain quality control analysis

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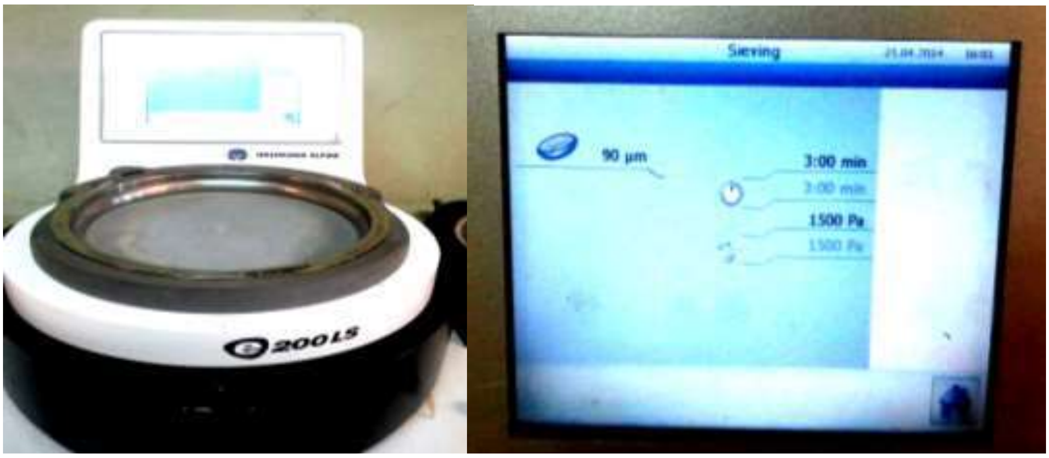

Hosokawa Alpine Sieve Machine

Fig.1. X-Ray Florescence Machine

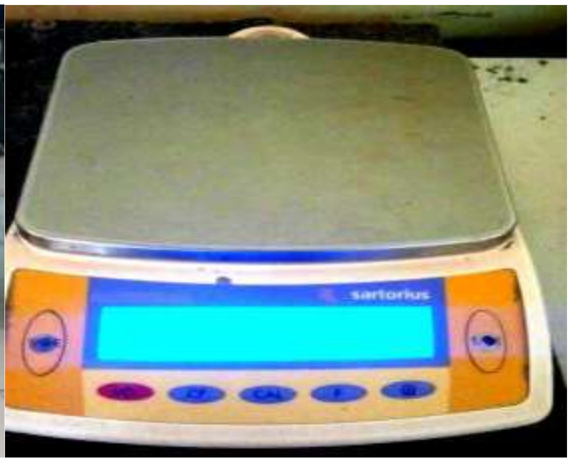

Fig.2. Weighing Balance

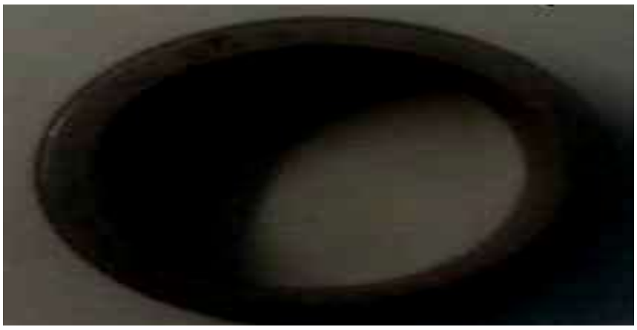

Fig. 3. Ring-shaped Pelletizer

B. Sieve Analysis

Raw meal feed were fed into kiln A2012 and kiln B2015 and then fired by natural gas to undergo pyro-process. Representative samples from the kilned feed were extracted from silo after every four hours and taken to laboratory for sieve analysis. Ten grams of representative sample were weighed out and poured on the 200µm sieve of the Hosokawa Alpine Sieve analyser and operated at 1500Pa for 3 minutes. The sample retained on the sieve were then collected and re-weighed. The percentage retained was then estimated using equation 8. The same procedure is repeated for 90µm sieve and the results are shown in Table 2.

$$\text{Percent retained } = \frac{\text{weight retained}}{\text{feed weight}} \times 100\% \quad (8)$$

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C. Chemical Analysis

Part of the sample collected during pyro-processing was milled using autogenous mill in the laboratory. After the milling process the sample was pelletized into a ring shape using a ring-shape pelletizer. The pelletized sample was placed in an X-ray fluorescence machine and set in operation for 2 minutes every four hours for 24 hours. The results of the chemical analysis are shown in Tables 3.

D. Method for Collecting Daily Production Parameter

The processes going on during clinker production are always displayed on the screen of a monitor controlled by adistributed control system (DCS) and monitored by kiln operators. The parameters necessary for controlling kiln operation are displayed on the monitor.Daily production parameters were obtained from the two operating kilns of Kiln A2012 and Kiln B2015.Data collected during clinker production are presented in Table 4.The parameters obtained are important for calculating heat consumption in Kcal/Kg of clinker using equation 9 for both operating kilns.

$$H = \frac{T_g \times C_V}{P \times 1000} \quad (9)$$

Where,
H = Heat Consumption (Kcal/Kg of Clinker)
T_g = Total Gas consumed (Nm^3)
C_V = Calorific value of gas (Kcal/ Nm^3)
P = Total Clinker Produced (tons)

E. Heat Optimization by Simplex Method

Data obtained through sieve analysis, chemical analysis, daily production and specific heat consumption are relevant to optimize the heat consumption using simplex method of linear programming. Based on design, the total production per day that is expected on both kilns is 13000 tons/day with LSF 94%, residue 2% using either by burning with gas or LPFO as fuel. Based on this condition in Obajana cement plant, heat consumption is expected to be ≤750 Kcal/Kg of clinker butby investigation,Obajana plant was discovered to exceed this design standard as shown in the data obtained in Table 5 which is a result from calculation carried out using equation 9 by substituting the parameters obtained on Table 4.

Applying Mark .A. Schulze 1998 simplex method of solving linear programming, heat consumption in both kilns were reduced by making heat consumption (H) as the objective function, LSF and particle size as constraints with clinker produced as variables. And as such the problem function is expressed as shown in equation 10.

Minimise

$$H = 766x_1 + 756x_2 \quad (10)$$

Where,
X_1 = Kiln A2012
X_2 = Kiln B2015
Subject to

$$6183x_1 + 6354x_2 \geq 13000$$
$$95.8x_1 + 95.5x_2 \geq 94$$
$$2.5x_1 + 2.2x_2 \geq 2$$
$$x_1, x_2 \geq 0$$

Adding Slacks Values:

$$6183x_1 + 6354x_2 + S_1 = 13000 \quad (11)$$
$$95.8x_1 + 95.5x_2 + S_2 = 94 \quad (12)$$
$$2.5x_1 + 2.2x_2 + S_3 = 2 \quad (13)$$

Where S_1, S_2 and S_3 are slack variables
$x_1, x_2, S_1, S_2, S_3 \geq 0$

III. RESULTS AND DISCUSSIONS

Results of Sieve Analysis:

The following tables contain results from sieve analysis;

Table 2:Result of Sieve Analysis

Hours	Kiln A2012 (% Retained)		Kiln B2015 (% Retained)	
	90 µm	200 µm	90µm	200µm
4	19.8	2.6	17.7	2.2
8	19.2	2.4	17.5	2.0
12	19.4	2.5	17.1	2.2
16	19.4	2.4	16.8	2.1
20	19.2	2.5	17.6	2.2
24	19.2	2.4	17.4	2.3
Average		**2.46**		**2.16**

Results of Chemical Analysis

The following tables contain results from chemical analysis;

Table 3: Result of X-Ray Analysis

Hours	Kiln A2012			Kiln B2015		
	SiO_2	Al_2O_3	LSF	SiO_2	Al_2O_3	LSF
4	2.36	1.42	95.73	2.35	1.32	95.56
8	2.34	1.4	95.86	2.26	1.33	95.85
12	2.35	1.41	95.84	2.27	1.30	95.39
16	2.44	1.39	95.69	2.31	1.37	95.60
20	2.31	1.40	95.9	2.32	1.38	95.

			1			71
24	2.41	1.43	95.90	2.33	1.37	94.83
Average			**95.8**			**95.5**

Calculation of Heat Consumption

Heat consumption for both kilns was calculated using equation (9) with the data obtained from daily production.

Table 4: Data of Production Parameters

Parameter	Unit value (A2012)	Unit value (B2015)
Clinker Produced	6183(tons/day)	6354 (tons/day)
Total Gas consumed	504020(Nm^3)	516450(Nm^3)
Calorific value of gas	9400 Kcal/Nm^3	9300 Kcal/Nm^3
Calculated Heat Consumption	766Kcal/Kg	756Kcal/Kg

Linear Programming

The result obtained from using Mark A. Shulze (1998) solution method solves the linear programming problem as shown in Tables 6, 7 and 8.

Table 5: Minimizing Using Simplex Methodof Linear Programming

Parameters	X_1	X_2	Design Standards
H	766	756	
LSF	95.8	95.5	94
RESIDUE	2.5	2.2	2
TPD	6183	6354	13000

Table 6: Result of Solving Linear Programming Problem

Basic	X_1	X_2	S_1	S_2	S_3	Value
S_1	6183	6354	1	0	0	13000
S_2	95.8	95.5	0	1	0	94
S_3	2.5	2.2	0	0	1	2
H	766	756	0	0	0	

Table 7: Result of Solving Linear Programming Problem

Basic	X_1	X_2	S_1	S_2	S_3	Value
S_1	0	912.96	1	0	-2473.2	8053.6
S_2	0	11.2	0	1	-38.32	17.36
X_1	1	0.88	0	0	0.4	0.8
H	0	81.92	0	0	306.4	- 612.8

Table 8: Result of Solving Linear Programming Problem

Basic	X_1	X_2	S_1	S_2	S_3	Value
S_1	0	0	1	-82.17	649.12	6638.51
X_2	0	1	0	0.09	-3.42	1.55
X_1	1	0	0	-0.08	3.41	-0.56
H	0	0	0	-7.37	-26.23	-739.78

Discussions

The results of the sieve analysis shows particle size of the material on 90µm and 200µm sieve taken after every four hour of the day. An average value of the results on either sieve sizes is important as an increase in particle size results to higher heat consumption and a reduction in particle size yields a lower heat consumption. The average value for Kiln A2012 is 2.46% and that of Kiln B is 2.16% which is found to be higher than the design particle size on 200µm sieve of 2%.

The result of the chemical analysis produced shows composition of silica, alumina and lime saturation factor (LSF) taken after every four hour of the day. An average value of the LSF is important to clinker production because an increase in LSF yields higher heat consumption and reduction in LSF yields lower heat consumption. The average value for Kiln A2012 is 95.8% and that of Kiln B2015 is 95.5% which is found to be higher than the design LSF of 94%.

Also from the kiln operation, the total quantity of fuel consumed were recorded as 504020 Nm^3 and 516450 Nm^3 and quantity of clinker produced were 6183tons/day and 6354tons/day for kilns A2012 and B2015 respectively. These values were used to calculate heat consumption on each kilns in Kcal/Kg clinker using calorific values of gas. The values obtained for heat consumption from the calculation are 766Kcal/Kg and 756Kcal/Kg respectively.

Data from the Table 5 were used to reduce heat consumption to 739.78 Kcal/Kg of Clinker using simplex method of solving linear programming problem. The mathematical model derived provided solution from the objective function that gives heat consumption at 739.78 Kcal/Kg of clinker which is a reduction when compared to 766Kcal/Kg and 756Kcal/Kg of the operational heat consumption.

IV. CONCLUSION AND RECOMMENDATIONS

Conclusion

The kilns under study were designed to maintained 750Kcal as total heat consumption per kilogram of clinker produced. After optimization, heat consumption was reduced to 739.78Kcal/Kg of Clinker. Based on these findings, Kiln feed must be ground finely enough, within the context of raw materials mineralogy and chemistry, to allow the particles react together within the time and temperature conditions in the kiln to achieve low heat consumption.

Recommendations

The chemical processes occurring inside a kiln are multi-dimensional and extremely complicated. There is no single factor that can be considered in isolation when seeking to optimize kiln performance and product quality, I therefore recommend that;

1. In optimizing a cement manufacturing plant, attention should therefore be giving to quarrying, crushing, and milling operation. Each stage should be examined in detail to know their impact on total plant operation and economics.

2. Particle size (Residue) and chemical composition of the material should be analysed and kept within their standard range.

4. For further research on this project, data should also be obtain from kilns with alternative fuel firing system to find out if the result achieved will conform with that of gas firing system.

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