Full Length Research Paper

Cement production optimization modeling: A case study BUA plant

Joseph Sunday Oyepata* and Otunuya Obodeh

Mechanical Engineering Department, Faculty of Engineering, Ambrose Alli University, Ekpoma, Edo State, Nigeria.

This paper deals with cement production optimization modeling using Particle Swarm Optimization (PSO) and the results was compared with Genetic Algorithm (GA) and Pattern Search (PS). This optimization modeling took into account mixtures of primary fuel (mineral coal, pet-coke and heavy oil) and its alternative fuel which is agricultural waste (rice husk, sugar waste and ground shell). The optimization simulation models predict the cost benefit to the manufacturer using alternative fuel, environmental impact to world and finally the quality of the cement produced to the end user. Production cost for one ton of cement using PSO ($23 = 4945), GA ($33 = 7095), PS (38.2 = 8170). The oxides in this research work met standard cement specification: Silica Modulus (M.S-2.9), Alumina Modulus (M.A- 1.3), Lime Saturation factor (LSF-93.3%). The results show that the cost of cement production can be reduced by 30 to 70% with the use of alternative fuel (Rice husk, Sugar cane waste, ground nut shell) and without greatly affecting the final product.

Key words: Fuel mixture, energy consumption, cement cost, cement quality.

INTRODUCTION

In cement production energy consumption takes the largest bulk of production cost. Due to this impact the cement manufacturers are always concerned about using alternative fuel mixture with low production cost without losing the quality of the final product and less environmental impact to the society. The process consists basically the replacement of the primary fuels by residues generated by other industries such as used tires, waste oils and other industrial wastes, agricultural waste, municipality waste, among others (Kleppinger, 1993).

This research work presents the possibility of using the mixture of mineral coal, petroleum coke, heavy oil, agricultural waste (rice husk, ground nut and sugar cane waste), etc. as fuel feed stock. This mixture is intended for a rotary kiln, clinker production; mainly dry process with a pre-heater and calciner. The optimization procedure will take into account process restrictions such as specific heat consumption, cement quality and environmental impact.

Primary fuels used in cement industry are mineral coal, petroleum coal, gas oil and natural gas. These provide most of the energy needs of the World today. Coal and natural gas are used in their natural forms, but petroleum

and other fossil fuels such as shale and bituminous sands require distillation and refinement to produce consumable fuels. These fuels exist in the following forms: Gaseous, liquid, and solid. The high cost of fossil fuels and most importantly, their damaging effect on the environment underscore the need to develop alternative fuel mixture for many industrial systems that rely on fossil fuels. Increased use of renewable and alternative fuels can extend life cycle of fossil fuel supplies and help resolve the present world global warming (Green House Gases) which is associated with the use of conventional fuels (Joseph and Obodeh, 2014).

Justification of the study

The cement manufacturing industry is under increasing pressure to reduce, cost of cement production and Green House Gas (GHG) emissions, such as carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NOx) (Conesa et al., 2008). It is estimated that 5% of global carbon dioxide emissions originate from cement production (Hendriks et al., 1998). These call for use of alternative fuel mixtures in cement plant which does not only afford considerable energy cost reduction, but also have significant ecological benefits of conserving non-renewable resources, the reduction of waste disposal requirements and reduction of Green House Gas emissions (Murray and Price, 2008). Use of low-grade alternative fuel mixtures in rotary kiln systems reduces GHG (Gabbard, 1990).

The finite nature of global fossil fuel resources, high prices and most importantly, their damaging effect on the environment underscore the need to develop alternative fuels for many industrial systems that rely on fossil fuels. Increased use of renewable and alternative fuels can extend fossil fuel supplies and help resolve air pollution problems associated with the use of conventional fuels (Kääntee et al., 2004).

Cement producers worldwide are striving to lower their production costs. One effective method of achieving this is the use of alternative fuels. Use of low-grade alternative fuels such as waste coal, tyres, sewage sludge, and biomass fuels (such as wood products, agricultural wastes, etc.) in precalciners is a viable option because combustion in a precalciner vessel takes place at a lower temperature (Roy, 2002; Smidth & Co., 2000). In precalciners where kiln exhaust gases pass through, the NOx emissions are much reduced due to re-burn reactions. There is an increased net global reduction in CO_2 emissions when waste is combusted in the cement kiln systems as opposed to dedicated incinerators, resulting in reduction in the CO_2 penalties. Since alternative fuels are often deemed cheaper than conventional fossil fuels, the possibility of a competitive edge is generated (Hewlett, 2004).

The use of alternative fuels in cement manufacture is also ecologically beneficial, for two reasons: The conservation of readily non-renewable resources, and the reduction of waste disposal requirements. The use of alternative fuels in European cement kilns saves fossil fuels equivalent to 2.5 million tonnes of coal per year (Cembureau, 1999).

Particle Swarm Optimization helps in the selection alternative fuel available among the spool of alternative fuel. The choice to be considered should at least have the following:

1. Kiln Stability
2. Best net calorific value
3. Economic and environmental importance

Particle swarm optimization helps in selecting raw materials simultaneously with fuels involving any combination and number of fossil fuels and waste derived fuels. The selection of the best possible solution is based on an economic objective function that accounts for the cost of raw materials, fossil fuels, alternative fuels and emissions.

Particle Swarm Optimization is initialized with a population of random solutions which is similar in all the evolutionary algorithms. Each individual solution flies in the problem space with a velocity which is adjusted depending on the experiences of the individual and the population. As mentioned earlier, PSO and its hybrids are gaining popularity in solving scheduling problems. A few of these works tackle the flow shop problem though application to hybrid flow-shops with multiprocessor tasks is relatively new (Yao et al., 2007).

This research work reviews in detail some of the main alternative fuels used in cement production and optitmization. It focuses on types of alternative fuels used, the environmental and socio-economic benefits of using alternative fuels, challenges associated with switching from conventional or fossil to alternative fuels, combustion characteristics of the alternative fuels concerned, and their effect on cement production and quality (Winter et al., 1997). The aim of this research work is to provide empirical evaluation of alternative fuels. It offers an invaluable source of information for cement manufacturers that are interested in using alternative fuels. Researchers and students would also find this information valuable for their academic work and development.

The successful conduct of this research work would lead to reduction of primary fuel consumed and substituting the primary fuel with alternative fuel mixtures in BUA cement plant, since energy cost is the largest variable of the production cost. Through the particle swarm optimization model, it is possible to foresee (Carpio et al., 2005) the raw material composition when alternative fuel mixtures has been decided to be used as secondary fuels in cement plant.

It is also possible to calculate the substitution levels of the primary fuel by alternative fuel mixtures derived

from agricultural wastes (rice husk, ground nut and sugar waste), being considered the acceptable and lowest pollutant emissions levels such as carbon dioxide, carbon monoxide and sulphur etc.

Objective of the study

The overall aim of the study is to develop readily and commercially available alternative fuel mixtures for achieving better stability of kiln operations, energy reduction and negative environmental impact minimization. The specific objectives are:

1. To carry out theoretical analysis and mathematical model using particle swarm optimization.
2. To determine the correlation between the cement standard results and empirical (experimental) results.
3. Comparing Particle Swarm Optimization model with other optimization model (Genetic Algorithms and Pattern Search)
4. To determine the effect of alternative fuel mixtures on; clinker quality, environmental impact, clinker production cost and cement production.

MATERIALS AND METHODS

The methodology of research is to use the Particle Swarm Optimization, Genetic Algorithm and Pattern Search simulation modeling. This will be generated from MATLAB software. Data used for this research was obtained from BUA cement plant laboratory and other foreign major cement group laboratory, such as Lafarge Group and Holcim Group, which are the largest cement manufacture in the world, while Flsmidth are the designer and manufacturer of cement equipment. The research results obtained (through optimization) will be compared with standard cement result.

Table 1 gives detail analysis of the raw material used to produce the raw meal for the kiln feed. Tables 2 and 3 are the detail analysis of primary fuels and alternative fuels (agricultural waste) used respectively for the production of cement.

Data processing

The method of analysis was the use of Particle Swarm Optimization, Genetic Algorithm and Pattern Search simulation model. This was generated from MATLAB software.
Different sets of data were used at each stage. Thus the data were used at each simulation stage are based on the Raw material percentage (%) and Alternative Fuel percentage (%).
The following training procedures were used:

1. A training set used in determining the Particle Swarm Optimization, Genetic Algorithm and Pattern Search simulation.
2. A validation set, used in estimating the Particle Swarm Optimization Genetic Algorithm and Pattern Search and decide when to start training.
3. Testing of the Particle swarm optimization Genetic Algorithm and Pattern Search tool with other optimization tools
4. Inputting the result of the simulations and also checking that all the constraint $X_1, X_2, X_3 \dots X_{10}$ are satisfied.

Raw materials and fuel mixture model

The material and fuel mixture optimization, was consider for the stable operation of the rotary kiln, the quality of the clinker produced, the minimum cost of the composition used and the electric power; all these variables are considered in the nonlinear model proposed through the following objective function, Equation (1) (Carpio, 2004, 2005).

$$C = \sum Pic * Xi + Pe * A * \exp^{(B.S)} \qquad (1)$$

The first term (linear) represents the raw materials and fuels (primary and alternative) costs used in the clinker production (p_i, is the raw materials and fuels costs i = 1,2....... 10, that participate in the burning, with their respective percentages $X_1, X_2,......X_{10}$). The objective function (C) of the model tried to obtain a minimum cost in the clinker production, considering the raw materials costs as well as the consumption of the energy required for grinding.
The second term (nonlinear) represents electricity cost (p_e) and the energy consumption required in kWh/t for the grinding process of a certain specific surface (S is the specific surface area in cm^2/g, A and B are constants that depend on the clinker composition).
Based on raw material, fuels chemical composition values and on the Equation (1), an objective function was set up, which represents costs minimization problem, considering the operational and environmental costs presented as it follows:

$$MINCost_1 X_1 + Cost_2 X_2 + Cost_3 X_3 + Cost_4 X_4 + Cost_5 X_5 + Cost_6 X_6 + Cost_7 X_7 + \qquad (2)$$
$$Cost_8 X_8 + Cost_9 X_9 + Cost_{10} X_{10} + Cost_{EE*} \left\{ (5.76(MS) - 5.82) * e^{(-0.2(MS)+0.98)*S} \right\}$$

$$M.S = \frac{(6.20X_1 + 63.62X_2 + 94.70X_3 + 3.6X_4 + 2.0X_5)}{(1.59X_1 + 26.84X_2 + 5.1X_3 + 93.95X_4 + 1.38X_5)} \qquad (3)$$

The constraints

$$52.18X_1 + 1.03X_2 + 1.01X_3 + 0.11X_4 + 0.18X_5 \geq 64 \qquad (4)$$

$$52.18X_1 + 1.03X_2 + 1.01X_3 + 0.11X_4 + 0.18X_5 \leq 71.2 \qquad (5)$$

$$6.20X_1 + 63.62X_2 + 94.70X_3 + 3.60X_4 + 2.0X_5 \geq 20.0 \qquad (6)$$

$$6.20X_1 + 63.62X_2 + 94.70X_3 + 3.60X_4 + 2.0X_5 \leq 24.50 \qquad (7)$$

$$1.12X_1 + 17.19X_2 + 3.67X_3 + 0.98X_4 + 1.07X_5 \geq 3.80 \qquad (8)$$

$$1.12X_1 + 17.19X_2 + 3.67X_3 + 0.98X_4 + 1.07X_5 \geq 6.83 \qquad (9)$$

$$0.47X_1 + 9.65X_2 + 1.43X_3 + 92.97X_4 + 0.31X_5 \geq 1.32 \qquad (10)$$

$$0.47X_1 + 9.65X_2 + 1.43X_3 + 92.97X_4 + 0.31X_5 \leq 5.40 \qquad (11)$$

$$0.80X_1 + 0.17X_3 + 0.08X_5 \leq 6.5 \qquad (12)$$

$$28.2X_5 + 33.7X_6 + 43X_7 + 13.517X_8 + 15.479X_9 + 17.8X_{10} = 3.60 \qquad (13)$$

$$1.30X_5 + 4.00X_6 + 1.54X_7 + 0.04X_8 + 0.17X_9 + 0.02X_{10} \leq 5.0 \qquad (14)$$

$$0.05X_1 + 3X_2 + 0.78X_3 \geq 0.20 \qquad (15)$$

Table 1. Data of raw meal material preparation used.

Material	Limestone	Clay	Laterite	Iron
Notation	X_1	X_2	X_3	X_4
Cao	52.18	1.03	1.0	0.11
SiO_2	6.20	63.62	94.70	3.60
Al_2O_3	1.12	17.19	3.67	0.98
Fe_2O_3	0.47	9.65	1.43	92.97
MgO	0.80	-	0.17	-
SO_3	0.05	3.00	0.78	-
Na_2O	0.07	0.30	0.50	-
K_2O	0.20	3.00	1.28	-

Table 2. Data of fuel composition employed as primary fuels.

Component	Mineral coal % weight	Pet coke % weight	Heavy oil uses % weight
Notation	X_5	X_6	X_7
C	70.60	89.50	84
H	4.30	3.08	12
N	1.20	1.71	Trace
O	11.8	1.11	1
S	1.30	4.00	3.00
Cl	0.07		
P_2O (In ash)	0.02		
Na_2O (In ash)	0.05		
K_2O (In ash)	0.12		
CaO (In ash)	0.18		
Fe_2O (In ash)	0.31		
Al_2O (In ash)	1.07		
SiO_2 (In ash)	2.00		
MgO (In ash)	0.08		
NiO (In ash)	-	0.04	
LHV (kJ/kg)	28,800	33,700	43,000

Table 3. Data of fuel composition employed as alternative fuels.

Component	Rice husk % weight	Sugar cane % weight	Ground nut shell % weight
Notation	X_8	X_9	X_{10}
C	37.48	41.16	45.9
H	4.41	5.08	5.34
O	33.27	37.42	36
N	0.17	0.14	1.09
S	0.04	0.02	0.01
Cl	0.09	0.01	
LHV(kJ/kg)	13,517	15,479	17.8

$$0.05X_1 + 3.0X_2 + 0.78X_3 \leq 2.07 \qquad (16)$$

$$0.07X_1 + 0.3X_2 + 0.5X_3 \geq 0.03 \qquad (17)$$

$$0.07X_1 + 0.3X_2 + 0.5X_3 \leq 0.33 \qquad (18)$$

$$0.2X_1 + 3X_2 + 1.28X_3 \geq 0.31 \qquad (19)$$

Table 4. Summary of result.

Objective function cost (C) = 22.9646 US$ = 4945(naira)	Oxides composition in clinker (%)	Modulus	Specific heat consumption = 3.6Gj/ton of clinker
$X_1 = 1.2495$ $X_2 = 0.1687$ $X_3 = 0.0436$ $X_4 = 0.0120$ $X_5 = 7.4977e\text{-}06$ $X_6 = 4.197e\text{-}08$ $X_7 = 3.898e\text{-}7$ $X_8 = 5.4881e\text{-}07$ $X_9 = 0.2326$ $X_{10} = 5.64749e\text{-}06$	CaO = 65.42 SiO = 22.65 Al_2O_3 = 4.5 Fe_2O_3 = 3.4 MgO = 1.01	M.S = $((SiO_2/(Fe_2O_3 + Al_2O_3))$ = 2.9 M.A = (Al_2O_3/Fe_2O3) = 1.3 LSF = $(((CaO+0.75)/((2.8SiO +(1.18Al_2O_3 *0.68Fe_2O_3)) *100\%$ = 93.3% S.R = $(SiO_2/((Fe_2O_3+ Al_2O_3))$ = 2.87 A.R = (Al_2O_3/Fe_2O_3) = 1.3	Mineral Coal X_5 =0.00021 Pet Coke X_6 = 0.000014 Heavy oil X_7 = 0.000017 Rice Husk X_8 = 0.0000074 Sugar cane waste X_9 = 3.6 Ground nut shell X_{10} = 0.0001

$$0.2X_1 + 3X_2 + 1.28X_3 \leq 1.82 \qquad (20)$$

EquationS (4) and (5) show the percentage of calcium oxide (CaO) contained in raw meal (clinker) 1 ton should be between 64 to 71.2%, Equation (6) and (7) show the percentage of silicon oxide (SiO_2) is contained in calcareous granules 1 ton should be between 20 to 25%. EquationS (8) and (9) show the percentage of aluminum trioxide (Al_2O_3) is contained in the calcareous grains per 1 ton should be between 4 and 7%. EquationS (10) and (11) show the percentage ferrous trioxide (Fe_2O_3) is contained in calcareous granules 1 ton should be between 2 to 5%. Equation (12) represents the percentage of magnesium should be less than or 6.50%. Equation (13) represents the heat value (Heating Value) used in the production of clinker, which requires an amount of heat equal to 3.6 GJ per ton of clinker. Equation (14) represents the percentage of sulfur (Sulphur) should be less than or equal to 5% of the sulfur from the fuel type. Equations (15) to (16) is the equation of an acid and a base of clinker, which comes from the ingredients used in the production of each species which is between 0.2 and 2.07%; Equation (17) to (18) is the best of sodium oxide (Na_2O) should be between 0.03 to 0.33% equations (18) to (19) values. Best of potassium oxide (K_2O) should be between 0.31 to 1.76% (Joseph and Obedeh, 2014).

RESULTS AND DISCUSSION

Optimization simulation runs results at 20 using Matlab software (Matlab 7.13). The grinding process of the cement a specific surface area S = 0.38 cm^2/g were used. The laptop used was Intel(R) Core™ i5-2540M CPU at 2.60 Hz RAM 4.00 GB, system type 32-bit operating system. In this case, the required chemical composition is sought for a cement type produced in a rotary kiln, dry process with heat specific consumption of 3600 clinker kJ/kg. The parameters of PSO, GE and PS used a population of 100 particles; $C_1 = C_2 = 2.0$; initial weighted (theta) of 0.9 with linear decline up to 0.3; search space of the variables to be optimized in the interval $0 < X_n < 3$, where n=1,.., 10. The cost used for this simulation are local market cost based in Nigeria where one (1) dollar $ = 215 naira.

The PSO has the lowest standard deviation and best average cost of producing one (1) ton of cement. All the constraints in the Equations (1) to (20) are all satisfied for PSO, GA and PS. To produce one (1) ton of cement using PSO, GA, PS model, it is expected that an average cost of $ 23 = 4945 naira, GA = $33.0 = 7095 naira and PS = $38.2 =8170 naira respectively are needed to produce one ton of cement. PS has the highest cost of producing one ton of cement Table 4.

The results in the above solution correspond to a final clinker composition, satisfying all objective function, constraint and restriction in the equation, with all parameters within standard cement allowable range. The solution for the optimization model is a function of the specific heat consumption and of the operational and environmental restrictions.

Conclusion

In cement production equipment optimization, the operating rate is different from design rate of the equipment. The design rate gives room for increasing or decreasing the feeding phase for the raw meal and the fuel usage in a rotary kiln allows some freedom for change in the composition of raw meal (raw mix and corrective materials) and fuel consumption. The aim is to minimize cost of production without losing the quality of the final production, prolong the life of the equipment, while satisfying the environmental and operational restriction. The alternative fuel used is an agricultural waste (sugar cane waste, ground nut shell and rice husks) and primary fuel are mineral coal, pet-coke and heavy oil. These Agricultural wastes present a great potential use in the production of cement via rotary kilns. A model is presented in this paper work in which the composition of the raw meal and the fuels mixtures enters as variables of a non-linear programing problem. The solution to this optimization problem finds composition values for the variable which will result is a cement production with low free lime (CaO) 0.5-1.5, less

environmental pollutants and good quality cement production.

Conflict of Interest

The authors have not declared any conflict of interest.

REFERENCES

Carpio RC, Silva RJ, Jorge AB (2004). Heavy metals influence in the mixture optimization of industrial waste fuels in cement industry, XXV Iberian Latin-American Congress on Computational Methods in Engineering, Recife, PE, Brazil.

Carpio RC, Coelho LS, Silva RJ, Jorge AB (2005).Case Study in Cement Kilns Alternative Secondary Fuels Mixing Using Sequential Quadratic Programming, Genetic Algorithms, and Differential Evolution, Proceedings of 6th World Congress on Structural and Multidisciplinary Optimization, Rio de Janeiro, RJ, Brazil.

Conesa JA, Font R, Fullana A (2008). Kinetic Model for the combustion of tyre wastes. Chemosphere 59:85-90.

CEMBUREAU (1999). Environmental Benefits of Using Alternative Fuels in Cement Production, 19:25-39.

Smidth FL and Co. (2000). Dry process kiln systems, technical brochure.

Gabbard WD, Gossman D (1990). Hazardous waste fuels and the cement kilns – The Incineration Alternative. ASTM Standardization News, September 1990. http://gcisolutions.com/HWF&CKS.htm, Accessed August 2014.

Gulyurtlu I, Boavida D, Abelha P, Lopes MH, Cabrita I (2005). Co-combustion of coal and meat and bone meal. Fuel 84:2137-2148.

Hendriks CA, Worrell E, De Jager D, Blok K, Riemer P (1998). Emission reduction of Greenhouse Gases from the cement industry presented at the 4th International conference on Greenhouse Gas Control Technologies, 30 August – 2 September 1998, Interlaken, Switzerland.

Hewlett PC (2004). LEA's Chemistry of Cement and Concrete (4th Ed). Elsevier Butterworth-Heinemann. 3:45-57.

Joseph SO, Obedeh O (2014). Optimizing Alternative Fuel mixtures in Cement Plant (BUA Cement Plant), Using Particle Swarm Optimization Method.

Kääntee U, Zevenhoven R, Backman R, Hupa M (2004). Cement manufacturing using alternative fuels and the advantages of process modeling. Fuel Process. Technol. 85:293-301.

Kleppinger EW (1993). Cement Clinker: an environmental sink for residues from hazardous waste treatment in cement kilns. Waste Manag. 13:553-572.

Murray A, Price L (2008). Use of Alternative Fuels in Cement Manufacture: Analysis of Fuel Characteristics and Feasibility for Use in the Chinese Cement Sector, Ernest Orlando Lawrence Berkeley National Laboratory, 10 March 2011.

Roy GR (2002). Petcoke combustion characteristics. World Cement 139:2-3.

Winter F, Prah ME, Hofbauer H (1997). Temperature in a fuel particle burning in a fluidized bed: The effects of drying, devolatilization and char combustion.

Yao K, Li F, Liu X (2007). An improved multi-particle swarm co-evolution algorithm. 3rd International Conference on Natural Computation. 3:51-55.