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The Impact of Fossil fuels and Agricultural Wastes Used as Energy Mix on Cement Production: Using Particle Swarm Optimization model

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Abstract

Co-processing from industrial generated waste has been used in the Ordinary Portland cement production companies. In-depth examination of the effects of using conventional fuel (mineral coal, pet-coke, heavy oil, and natural gas) and agricultural waste is presented in this research, along with prospects for employing both for the optimization of cement production (sugar waste and ground nut shell). This mixture is meant to be used in a dry process rotary kiln for producing clinker. Particle Swarm Optimization was the optimization model employed (PSO). The results gotten from the (PSO) analyses help in calculating the substitution levels of the primary fuels with alternative fuel mixes derived from agricultural wastes (husk, rice, ground nut shell and sugar wastes), with was considered to have lower pollutants level such as carbon dioxide, carbon monoxide and sulphur etc. The end product's (cement) specific surface area changed from 0.35 cm^2/g to 0.38 cm^2/g, resulting in a modest increase in energy consumption, longer clinker grinding time, a decrease in production output, and a faster rate of wear part inside the mills and its auxiliaries.

1. Introduction

The cement industry is constantly concerned with employing low-cost alternative fuels since producing cement uses a lot of energy. As a result, other fuel mixtures can be used without lowering the quality of the finished products. The procedure simply entails replacing a portion of the conventional fuel with waste products produced by other industries, such as used tires, waste lubricants, agricultural waste, and other industrial waste [1-3]. One of the most significant building materials in the world is cement. The process of making cement is an energy-intensive one, requiring roughly 3.3–3.6 GJ of thermal energy per ton of clinker produced. About 90–120 kWh of electrical energy is used for every ton of cement, [4-5].

Coal has been a major fuel used in the cement industries. It has been successfully utilized to fire cement-making kilns with a broad variety of alternative fuels, including natural gas, heavy oil, liquid waste, solid waste, and petroleum coke, either separately or in various combinations, [6, 7].

The majority of the world's current energy needs are met by fossil fuels including coal, petroleum, and natural gas. Natural forms of coal and gas are used, although distillation and refinement are needed to turn petroleum and other fossil fuels, like shale and bituminous sands, into useful fuels, [8]. These fuels are available in solid, liquid, and gas forms. The necessity to provide alternative fuel mixtures for several industrial systems that rely on fossil fuels is highlighted by the limited nature of the world's fossil fuel resources, their high prices, and—most importantly—their detrimental impact on the environment, [9]. Increased usage of alternative and renewable fuels can assist in reducing air pollution caused by traditional fuel use and extend the supply of fossil fuels [10 - 13].

This research tends to reviews in details some agricultural waste as alternative fuel combinations that can be employed for OPC production and energy optimization in cement plants. It also focuses on the advantages of using alternative fuel mixtures from an environmental and socioeconomic perspective, the difficulties of switching from conventional or fossil fuels to alternative fuels, the combustion characteristics of the alternative fuel mixture, and their impact on cement production and quality.

The cement industries are under global pressure to reduce Green House Gas (emission) effect that is currently posing serious challenges to the some of this emission are such as nitrogen oxide (NOx), carbon dioxide (CO_2), carbon monoxide (CO), Chloride and Fluoride, [14]. It is estimated that 5% of global carbon dioxide emissions originate from cement production [1, 15]. These gives rise to the source of more sustainable and environmental friendly alternative fuel mixtures to be use in cement plants which is not only affordable in terms of cost reduction but also have significant ecological benefit of conserving non-renewable resources, reduction of waste control and also reduction on Green House Gas emission, [9, 16]

This research work examines the potential of blending some fossil source of fueling (heavy oil, coal, petroleum coke) and agricultural waste (such as rice husk, groundnut shells, and sugar cane waste) as a fuel feedstock. This mixture will be used to fire a rotary kiln for the manufacturing of Ordinary Portland Cement (OPC), which involves primarily dry process and a pre-heater. Process limitations, such as particular heat consumption, cement quality, and environmental impact, will be taken into account during the optimization process.

2. Materials & Methodology

2.1 Material and Data Collection

Raw materials used for this research were obtained from an existing cement plant (Nigeria) laboratory analysis. Table 1, shows the percentage of oxide composition contained in the production of clinker, Table 2 and Table 3, shows the chemical (percentage weights) contents of the fuel used for firing the rotary kiln.

Table 1: List of Raw mix material Preparation Used.

Material	Limestone	Clay	Laterite	Iron
Notation	X_1	X_2	X_3	X_4
Cao	52.19	1.04	1.00	0.13
SiO_2	6.22	63.64	94.90	3.62
Al_2O_3	1.14	17.20	3.69	0.99
Fe_2O_3	0.48	9.77	1.45	92.99
MgO	0.80	-	0.18	-

SO_3	0.04	3.05	0.79	-
Na_2O	0.05	0.43	0.50	-
K_2O	0.11	3.50	1.29	-

Table 2: List 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	70.61	89.50	84
H	4.32	3.08	12
N	1.22	1.71	Trace
O	11.7	1.11	1
S	1.33	4.00	3.00
Cl	0.08	-	-
P_2O(In ash)	0.03	-	-
Na_2O(In ash)	0.05	-	-
K_2O(In ash)	0.14	-	-
CaO(In ash)	0.19	-	-
Fe_2O(In ash)	0.33	-	-
Al_2O(In ash)	1.06	-	-
SiO_2(In ash)	2.20	-	-
MgO(In ash)	0.09	-	-
NiO(In ash)	-	0.04	-
LHV(kJ/kg)	28,820	33,710	42,999

Table 3: Data of Fuel composition employed as Alternative fuels.

Component	Natural gas % weight	Sugar cane waste % weight	Rice husk % weight
Notation	X_8	X_9	X_{10}
C	73	41.17	45.8
H	25	5.09	5.36
O	5.4	37.00	36
N	0.00	0.15	1.07
S	0.0	0.02	0.02
Cl	0.0	0.02	-
LHV(kJ/kg)	50.67	15,479	17.9

2.2 Data Processing

The goal of the data analysis was to forecast the personal best (p-best) and global best (g-best) low-calorie alternative fuel (LCV).

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. The training, validation, and testing of this model were all part of its development. At each level, various sets of data were employed. Thus, the data were used at each simulation stage based on the Raw material percentage (%), Primary Fuels percentage and Alternative (%), [17- 24].

2.3. Raw Mix and Fuel mixtures model

The material and fuel mixture optimization were considered 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 non-linear model proposed through the following objective function, Eq. (1.0), [18].

$$C = \sum Pic * Xi + Pe * A * \exp^{(B.S)} \tag{1.0}$$

The first term "linear" represents the raw mix and fuels (Traditional and alternative) costs used for the production clinker (p_i, is the raw materials and fuels costs i = 1,2....... 10, participated in the burning process, with respective percentages of X_1, X_2, ...X_{10}). Objective function (C) of the model will tries to obtain a minimum cost on the clinker production, considering the raw mix design cost as well as the specific energy consumption in grinding the clinker to final products.
The second term "non-linear" represents electricity cost (p_e) and the energy required in kWh/t for the grinding clinker to powdered cement with 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), [1, 17, 18].
Based on raw mix, fuels chemical composition values as shown on equation (2.0) which represents minimum costs problem, considering the operational and the environmental costs as shown in equation (3.0) and (20.0) [17, 18]:

$$MINCost_1 X_1 + Cost_2 X_2 + Cost_3 X_3 + Cost_4 X_4 + Cost_5 X_5 + Cost_6 X_6 + Cost_7 X_7 + Cost_8 X_8 + Cost_9 X_9 + Cost_{10} + Cost_{EE*} \left\{ (5.76(MS) - 5.82) * e^{(-0.2(MS)+0.98)*S} \right\} \quad (2.0)$$

$$M.S = \frac{(6.20X_1 + 63.62X_2 + 94.70X_3 + 3.6X_4 + 2.0X_5)}{(1.59X_1 + 26.84X_2 + 5.1X_3 + 93.95X_4 + 1.38X_5)} \quad (3.0)$$

The Constraints

$$52.18X_1 + 1.03X_2 + 1.01X_3 + 0.11X_4 + 0.18X_5 \geq 64 \quad (4.0)$$
$$52.18X_1 + 1.03X_2 + 1.01X_3 + 0.11X_4 + 0.18X_5 \leq 71.2 \quad (5.0)$$
$$6.20X_1 + 63.62X_2 + 94.70X_3 + 3.60X_4 + 2.0X_5 \geq 20.0 \quad (6.0)$$
$$6.20X_1 + 63.62X_2 + 94.70X_3 + 3.60X_4 + 2.0X_5 \leq 24.50 \quad (7.0)$$
$$1.12X_1 + 17.19X_2 + 3.67X_3 + 0.98X_4 + 1.07X_5 \geq 3.80 \quad (8.0)$$
$$1.12X_1 + 17.19X_2 + 3.67X_3 + 0.98X_4 + 1.07X_5 \geq 6.83 \quad (9.0)$$
$$0.47X_1 + 9.65X_2 + 1.43X_3 + 92.97X_4 + 0.31X_5 \geq 1.32 \quad (10.0)$$
$$0.47X_1 + 9.65X_2 + 1.43X_3 + 92.97X_4 + 0.31X_5 \leq 5.40 \quad (11.0)$$
$$0.80X_1 + 0.17X_3 + 0.08X_5 \leq 6.5 \quad (12.0)$$
$$28.2X_5 + 33.7X_6 + 43X_7 + 50.2X_8 + 15.5X_9 + 17.8X_{10} = 3.6 \quad (13.0)$$
$$1.30X_5 + 4.00X_6 + 1.54X_7 + 0.04X_8 + 0.17X_9 + 0.02X_{10} \leq 5.0 \quad (14.0)$$
$$0.05X_1 + 3X_2 + 0.78X_3 \geq 0.20 \quad (15.0)$$
$$0.05X_1 + 3.0X_2 + 0.78X_3 \leq 2.07 \quad (16.0)$$
$$0.07X_1 + 0.3X_2 + 0.5X_3 \geq 0.03 \quad (17.0)$$
$$0.07X_1 + 0.3X_2 + 0.5X_3 \leq 0.33 \quad (18.0)$$
$$0.2X_1 + 3X_2 + 1.28X_3 \geq 0.31 \quad (19.0)$$
$$0.2X_1 + 3X_2 + 1.28X_3 \leq 1.82 \quad (20.0)$$

Equation (4.0) and equation(5.0) shows the percentage of calcium oxide (CaO) contained in raw meal (clinker) for one ton should be between 64% - 71 %, equation (6.0) and equation(7.0) shows the percentage of silicon oxide (SiO_2) contained in calcareous granules one ton should be between 20 % - 25 %, equation (8.0) and equation (9.0) shows the percentage of aluminum trioxide (Al_2O_3) contained in the calcareous grains per one ton should be between 4 % - 7 %, equation (10.0) and equation(11.0) shows the percentage ferrous trioxide (Fe_2O_3) contained in calcareous granules one ton should be between 2 % - 5 %, equation (12.0) represents the percentage of magnesium should be less than or 6.50% . Equation (13.0) represents the heat value (Heating Value) used in the production of clinker which requires an amount of heat equal to 3.6 to 3.8 GJ per ton of clinker Equation (14.0) represents the percentage of sulfur (Sulphur) should be less than or equal to 5 % of the sulfur from the fuel type, equations (15.0) to equation (16.0) 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 % - 2.07%, equation (17.0) to equation (18.0) is the best of sodium oxide (Na_2O) should be between 0.03% - 0.33%, equation (18.0) to equation (20.0) values . Best of potassium oxide (K_2O) should be between 0.31% - 1.76 %, [1].

3.0 Results and Discussion

A Matlab software was used for simulation and for the purpose of this research a set target of Blaine or specific surface area S = 0.35 and 0.38 cm^2/g were used. Intel(R) laptop Core™ i5-2540M CPU at 2.60Hz RAM 4.00GB, 32-bit operating system. A raw meal sample used for this research has the chemical composition as shown on Table 4 it is was used for the purpose of this research in rotary kiln, dry process with heat specific heat consumption of 3.6 to 3.8 GJ per ton of clinker produced.
The exchange rate used for the simulation is the current Central Bank of Nigeria exchange rate as at October 2022, in Nigeria where one (1) dollar $ = ₦ 465 naira. The parameters of Particle Swarm Optimization uses a population of 100 particles; $C_1 = C_2 = 2.0$; initial weighted 0.9 and a linear decline of 0.3; the search spaces of the variables to be optimized are in the interval $0 < X_n < 3$, where n =1...9,10. Figure 1, shows the PSO simulation results template and for the purpose this research 20 runs of PSO was carried out.

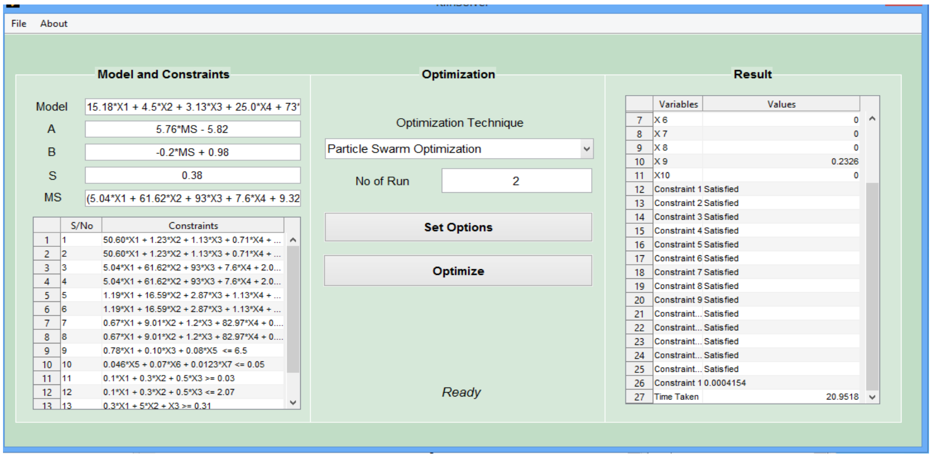

Figure 1. Particle Swarm Optimization simulation model used.

Table 4: 20 Runs for Particle Swarm Optimization Results using Specific surface area (S) of $0.35cm^2/g$ and $0.38cm^2/g$.

Restrictions (Xi)	Specific Surface area(S)= 0.35 cm^2/g	Specific Surface area(S)= 0.38 cm^2/g
X_1	1.2495	1.2219
X_2	0.1687	0.1887
X_3	0.0436	0.0470
X_4	0.0120	0.0108
X_5	7.4977e-06	5.9679e-04
X_6	4.1973e-08	5.0765e-04
X_7	3.8986e-07	1.2967e-06
X_8	5.4881e-07	0.0046
X_9	0.2326	0.2251
X_{10}	5.6479e-06	0.0011

Table 5: 20 runs PSO: Specific surface area 0.38 cm^2/g, Material Composition and Constraints Results

Restrictions (Xi)	PSO	Material	Blain(cm^2/g)	Constraint	Material Composition	Inference
X_1	1.2219	CaO	0.38	64.00≤ X_1≤71.20%	64.00%	Satisfied
X_2	0.1887	SiO_2	0.38	20.00≤ X_2≤24.50%	24.07%	Satisfied
X_3	0.0470	Al_2O_3	0.38	3.80 ≤ X_3≤ 6.83%	4.81%	Satisfied
X_4	0.0108	Fe_2O_3	0.38	1.32≤ X_4 ≤5.40%	3.47%	Satisfied
X_5	5.9679e-04	MgO	0.38	MgO ≤6.5%	0.99%	Satisfied
X_6	5.0765e-04	HEAT VALUE	0.38	HEAT VALUE = 3.6GJ	3.77	Satisfied
X_7	1.2967e-06	SO_3	0.38	SO_3 ≤5	0.04	Satisfied
X_8	0.0046	ACID AND BASE	0.38	0.20≤ ACID AND BASE ≤2.07%	0.66%	Satisfied
X_9	0.2251	Na_2O	0.38	0.03≤ Na_2O ≤0.33%	0.17%	Satisfied
X_{10}	0.0011	K_2O	0.38	0.31≤ K_2O ≤1.82%	0.87%	Satisfied

Table 6: 20 runs PSO: Specific surface area 0.35 cm^2/g, Material Composition and Constraints results

Restriction (Xi)	PSO	Material	Blain(cm^2/g)	Constraint	Material Composition	Inference
X_1	1.2495	CaO	0.35	64.00≤ X_1≤71.20%	65.42	Satisfied
X_2	0.1687	SiO_2	0.35	20.00≤ X_2≤24.50%	22.65	Satisfied
X_3	0.0436	Al_2O_3	0.35	3.80≤ X_3≤6.83%	4.47	Satisfied
X_4	0.0120	Fe_2O_3	0.35	1.32≤ X_4≤5.40%	3.39	Satisfied
X_5	7.4977e-06	MgO	0.35	MgO≤6.5%	1.01	Satisfied
X_6	4.1973e-08	HEAT VALUE	0.35	HEAT VALUE =3.6 to 3.8 GJ	3.61	Satisfied
X_7	3.8986e-07	SO_3	0.35	SO_3≤5%	0.04	Satisfied
X_8	5.4881e-07	ACID AND BASE	0.35	0.20≤ ACID AND BASE ≤2.07%	0.60	Satisfied
X_9	0.2326	Na_2O	0.35	0.03≤ Na_2O ≤0.33%	0.16	Satisfied
X_{10}	5.6479e-06	K_2O	0.35	0.31≤ K_2O ≤1.82%	0.81	Satisfied

The above results on 20 runs simulation model using 0.35 cm^2/g and 0.38 cm^2/g, the constraints and restriction in equation (4) to (20) are all satisfied. Particle Swarm Optimization tool uses sugar cane waste (X_9) 99.9% as it major source of fuel in generating energies for firing the rotary kiln for the clinker production and 0.1% of other sources fuel.
Figure 2, shows the raw mix percentage versus raw meal quality percentage produced out of raw mix and Figure 3, shows qualities of the clinker produced against the quality parameters for the clinker produced.

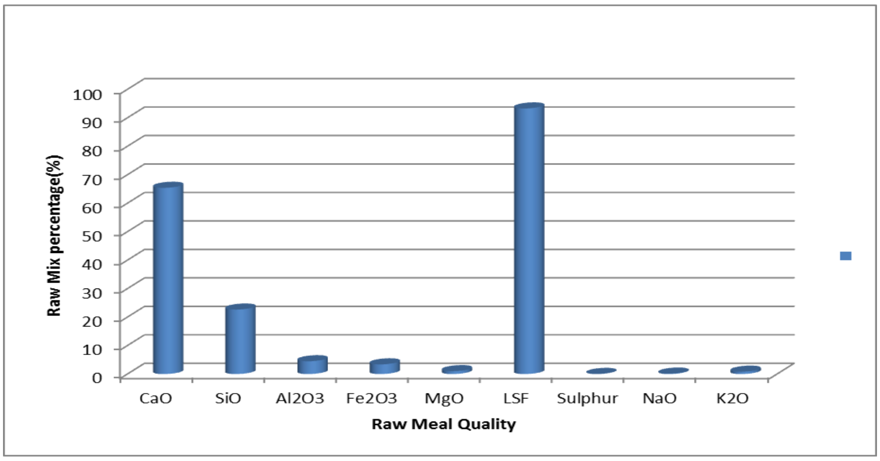

Figure 2: Raw mix percentage (%) VS Raw meal quality

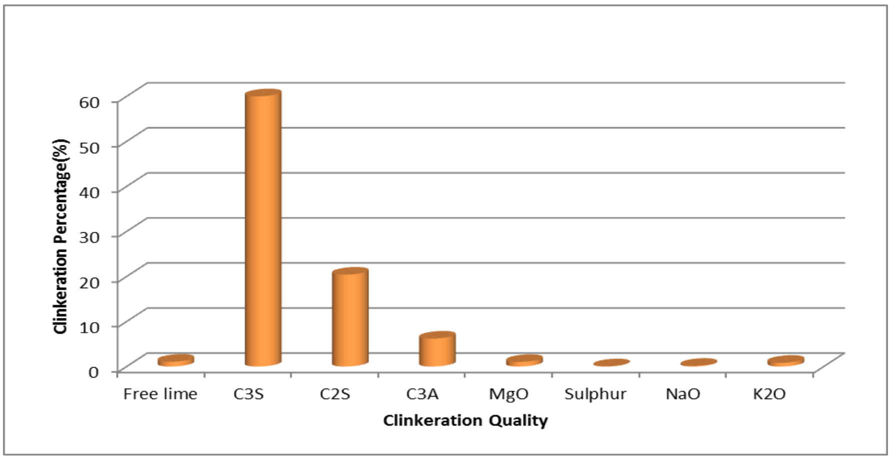

Figure 3: Clinker quality after firing the raw meal.

The simulation results shown in Fig.2 and Fig.3 proved that the mixture of primary fuel (mineral coal, pet-coke, heavy oil and natural gas) and agricultural waste (sugar cane waste and ground nut shell), did not affect the quality of the clinker produced greatly.

The research results met the following requirement for a good Ordinary Portland Cement as these quality ranges for C_3S (35-70%), C_2S (20-45%), C_3A(3-18%),C_4AF(1-15%), CaO (0.5-2%)), and also low cost of clinker production.
Silica Modulus (M.S) = 2.28
Alumina Modulus (M.A) = 1.3
Lime saturation factor (LSF) = 93.0%
Alumina ratio (A.R) = 1.3
Silica ratio (S.R) = 2.86.

The coating inside the rotary kiln is slightly thin base on the result of the alumina ratio and silica ratio, as shown in equation (21.0) to (24.0).

C_3S = 4.07 CaO – 7.6 SiO_2 – 6.72 Al_2O_3 – 1.43 Fe_2O_3 = 59 (21.0)

C_2S = 8.6 SiO_2 + 5.07 Al2O$_3$ + 1.08 Fe_2O_3 - 3.07 CaO = 20.4 (22.0)

Or 2.87 SiO_2 – 0.754 C_3S

C_3A = 2.65 Al_2O_3 – 1.69 Fe_2O_3 = 6.2 (23.0)

C_4AF = 3.04 Fe_2O_3 = 10.336 (24.0)

- C_3S Contributes early day and late strength (1-2 day) and Increases heat of hydration
- C_2S Contributes late strength (28 days)
- C_3A Contributes to early strength (1 – 3days), Increases heat of hydration, and Impairs resistance to sulphate attack
- C_4AF Lesser effect

The above results Table 5 and Table 6 indicates the quality cement can be produce from the design raw mix that was designed for the production of good cement. The solution for the optimization model is a function of the specific heat consumption and of the operational and environmental restrictions.

The optimization simulation results also shows that quality cement can be produced using the right proportion agricultural waste as substitute of fuel in a rotary kiln operation.

4.0 Conclusion

Impacts of Fuel Mixture (fossil fuels and agricultural waste) on Cement Production using PSO as model used for this research, clearly shows that some of the agriculture waste that are been continuously burnt annually by our farmers and agricultural manufacturing company can be converted to another source of revenues for both the agricultural manufacturers and farmers instead burning it. The cement industries are in continuous search for ways in reducing the use of fossil fuels in heat generation for kiln firing. This alternative for fuel mixtures will also contribution to the reduction of carbon emission and a reduction on Green House Gas (GHG) emission. PSO presents the possibilities to foresee the impacts of the fuel mixture on raw mix designs composition when considering the use of agricultural waste as a secondary fuel in the production of cement. It is also feasible to calculate the substitution ratio of the primary fuel to alternative fuel derived from the agricultural waste.

Finally, increasing the Blaine or specific surface area of the final products (cement) from 0.35cm^2/g to 0.38cm^2/g has some slight increase on the specific heat consumption as shown on Table 5 (0.38 cm^2/g) as 3.77 GJ per ton of clinker produced and against Table 6 (0.35 cm2/g) which uses 3.61 GJ per ton of clinker produced.

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